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THESIS

MEASURING COMBAT LOGISTICS FORCE (CLF) ADEQUACY IN SUPPORTING NAVAL OPERATIONS

by

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March 2012

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MEASURING COMBAT LOGISTICS FORCE (CLF) ADEQUACY IN SUPPORTING NAVAL OPERATIONS

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ABSTRACT

We use the existing outputs of the Combat Logistics Force (CLF) Planner tool to: (1) assess the minimum level of support required for a specified force in a multi-stage naval combat scenario and (2) compare CLF adequacy, surplus mission capability, and logistics shortfalls that a minimum level of support provides to combat forces of varying compositions. We examine the potential impact of the transition from a traditional nuclear-powered aircraft carrier strike group to a more distributed conventionally-powered one. We find that the logistical demands of a small conventionally-powered carrier strike group with comparable striking power require significant increases in CLF end strength, and therefore that logistical supportability must be an integral part of future fleet planning.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASW	Anti-Submarine Warfare
BG	Battle Group
CBO	Congressional Budget Office
CLF	Combat Logistics Force
CG	Guided Missile Cruiser
CNO	Chief of Naval Operations
CSG	Carrier Strike Group
CVL	Aircraft Carrier, Light
CVN	Aircraft Carrier, Nuclear
DDG	Guided Missile Destroyer
DoN	Department of the Navy
FFG	Guided Missile Frigate
HADR	Humanitarian Assistance Disaster Relief
LCS	Littoral Combat Ship
MIP	Mixed Integer Program
NNFM	New Navy Fighting Machine
NPS	Naval Postgraduate School
OSD	Office of the Secretary of Defense
TBMD	Theater Ballistic Missile Defense

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EXECUTIVE SUMMARY

Over the past few years, United States maritime strategy has placed increased emphasis on forward presence, peace-keeping and cooperative engagement with regional strategic partners. Concerned that the current U.S. naval fleet might not be up to these new tasks, the Office of Net Assessment of the Office of the Secretary of Defense commissioned the Naval Postgraduate School (NPS) to conduct a study outlining the type of future fleet that might best meet the needs of evolving U.S. maritime strategy.

The resulting study proposes a compelling argument for a distributed, "bimodal" (featuring distinct littoral and open-ocean elements) force that is significantly different from the present U.S. fleet. The logistical supportability of this new fleet, however, is left as an open question by the original NPS study. Because we feel adequate logistical support is a necessary condition for operational success, the purpose of this research is to help fill that void by performing an initial analysis of the ability of the Combat Logistics Force (CLF) as currently comprised to support key elements of this new distributed fleet.

In order to answer this question, we first look more closely at what the concept of "adequate support" entails. Previous work was focused on simple "go or no-go" analysis that is sufficient for answering the fundamental question "is it supportable?", but falls short in providing the additional insight needed to make informed choices between potential alternatives such as those encountered when planning support for a hypothetical future fleet. We use an existing mixed integer optimization-based planning tool in a manner that promotes analytic flexibility and yields supplemental statistics that provide these needed insights.

To accomplish this, a notional 100-day "war at sea" scenario is developed and used to exercise sets of notional combatant task groups drawn from both the existing U.S. fleet and the future fleet as proposed by the NPS study. These notional task groups are then run through our planning tool to determine the minimum level of CLF support required for mission success. In addition to traditional "go or no-go" feasibility

assessments, we draw additional rate statistics from the output of the model to serve as proxies for potential surplus logistics support capacity and operational mission flexibility of the combatant ships assigned.

We find that the introduction of conventionally powered light aircraft carriers of 30,000–40,000 tons that forms the cornerstone of the NPS study will create a crippling burden for the present-day CLF. Further, we find that the reduced logistical footprint of the smaller escort vessels proposed does not appear to be sufficient to offset the additional demands imposed by the conventionally fueled carriers employed. From this, we conclude that the potential deficiencies in the ability of the CLF to support this new fleet are too large to justify the "wait and see" approach towards future CLF force structure adopted by the original NPS study. We also assess the pros and cons of the study method developed here, finding that the additional flexibility and insights provide sufficient justification for the additional analyst workload that this method entails.

ACKNOWLEDGMENTS

This research would not have been possible without the assistance of Captain (retired) Wayne Hughes, both for his work in spearheading the study which provided the inspiration for my work and for his invaluable help along the way. His enthusiasm for the project was infectious, providing much needed moral support at those times when I started to feel that perhaps I had headed down the wrong path. I am also deeply indebted to Professor Brown for his vast technical expertise with the CLF Planner and for providing a calming counterbalance to Captain Hughes' enthusiasm.

The heretofore unnamed conspirators that have helped out along the way are legion. Space and my porous memory prevent me from naming them all, but a few warrant special mention. During the early days when I struggled to get the models up and running, Professor Matt Carlyle provided important insight into what was going on "under the hood." Commander Walt DeGrange and Commander Pat Burson also deserve mention, both for helping me to think about the problem correctly and for the offhand general advice and mentorship they have provided.

Most of all, however, I'd like to thank my wife, Christina. I know this tour has been tough for you, and that despite being on shore duty I haven't been nearly as accessible as I would have liked. As always, you've been the glue that holds it all together. Thanks for putting up with me.

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I. BACKGROUND

A. PURPOSE OF THIS RESEARCH

In response to the challenges of meeting the new maritime strategy laid out in *A Cooperative Strategy for 21st Century Sea Power* (SECNAV, 2007), the Office of Net Assessment of the Office of the Secretary of Defense (OSD) commissioned the Naval Postgraduate School to conduct a study of what sort of force structure might best support it. The resulting report, *The New Navy Fighting Machine: A Study of the Connections Between Contemporary Policy, Strategy, Sea Power, Naval Operations, and the Composition of the United States Fleet* (Hughes, 2009), hereafter referred to as the NNFM, proposes a radically different force structure from that which we have today. As it provides only archetypes of the types of ships that might be added to most efficiently deliver the capabilities required in support the new maritime strategy, the adequacy of the existing Combat Logistics Force (CLF) to support the new fleet was left as an open question pending further development of the ships proposed. The purpose of this research is to help fill that void by performing an initial analysis of the ability of the CLF as currently comprised to support one of the key enablers of the bimodal fleet described by the NNFM study—the introduction of smaller, conventionally-powered "light" aircraft carriers (CVL) of about 30,000 tons, each carrying one-third as many aircraft as the nuclear-powered aircraft carriers (CVN) currently employed.

Toward this end, we use the outputs of an existing optimization-based CLF scheduling and force planning tool (CLF Planner). The goals of this are two-fold: (1) assess the minimum level of logistical support (in terms of number of CLF ships required) for a specified force in a multi-stage scenario, and (2) derive metrics from the resulting notional replenishment schedules to assess and compare surplus mission capability (both combatant and logistical) that this minimum level of support provides to combat forces of varying compositions. We find that supporting the logistic demands of a CVL-based carried strike group with comparable striking power to a current nuclear (CVN) based group require significant increases to the CLF end strength, and therefore logistical supportability must be made an integral part of any future fleet planning.

B. THE CHANGING FACE OF U.S. NAVAL STRATEGY

In 2007, the service chiefs of the U.S. Navy, Marine Corps, and Coast Guard issued a new document outlining their vision for the Department of the Navy's (DoN) role in the future of United States military strategy. Building upon the foundation laid in Admiral Vern Clark's "Sea Power 21" (2002), *A Cooperative Strategy for 21st Century Sea Power* (SECNAV, 2007) outlines a transformative view of the role of maritime power in the coming years. The fleet of the future will be "characterized by regionally concentrated, forward-deployed task forces with the combat power to limit regional conflict, deter major power war, and … win our Nation's wars as part of a joint or combined campaign" as well as providing

> persistent, mission-tailored maritime forces… globally distributed in order to contribute to homeland defense-in-depth, foster and sustain cooperative relationships with [our] international partners, and prevent of mitigate disruptions and crises. (SECNAV, 2007, p. 8)

Meeting these objectives requires growth in several capabilities. In addition to the well established functions of forward presence and power projection ashore, future U.S. maritime forces will increasingly be called on to serve in a deterrent capacity through theater ballistic missile defense (TBMD) (SECNAV, 2007, p. 13). In order to ensure our continued control of the seas, U.S. anti-submarine warfare (ASW) capabilities must be improved and expanded to counter the proliferation of modern diesel-electric and nuclear-powered submarines (SECNAV, 2007, p.13). The Navy of the future will also continue to play an increased role in global maritime security (counter piracy and smuggling interdiction) and humanitarian assistance and disaster relief (HADR) operations (SECNAV, 2007, p. 14).

The Chief of Naval Operations (CNO) plan to provide these capabilities is outlined in the 2011 long-range ship construction plan (OPNAV N8F, 2010) prepared for Congress. Over the next 30 years, 256 vessels—roughly 90% of the current fleet of 284—are scheduled to be retired from service (OPNAV N8F, 2010, p. 21). These are to be replaced by 276 new vessels (OPNAV N8F, 2010, p. 18), with "spiral upgrades" and service life extensions for existing platforms serving to fill the projected gaps in numbers and capabilities (OPNAV N8F, 2010, p. 9).

This plan carries risks, of course. Responsibility for many of the expanded mission areas outlined in *A Cooperative Strategy for 21st Century Sea Power* will fall squarely on the shoulders of the cruisers (CG) and destroyers (DDG) that form the numerical backbone of the fleet. Increased requirements for these multi-mission ships to provide forward presence and TBMD while still performing their traditional roles in strike group operations is expected to provide "additional pressure" on the baseline inventory of 88 ships and may require a choice between purchasing additional ships or "redistributing assets currently being employed for missions of lesser priority" (OPNAV N8F, 2010, p. 14). Put another way, the Navy foresees that our current fleet of the future may not be big enough to meet its commitments.

C. THE NEW NAVY FIGHTING MACHINE (NNFM)

Perhaps recognizing the challenges of meeting this new maritime strategy, the Office of the Secretary of Defense's (OSD) Office of Net Assessment commissioned the Naval Postgraduate School to conduct a study of what sort of force structure might best support it. The resulting report (Hughes, 2009) proposes a radically different force structure from the current fleet. It proposes a "wider mix of ships, in a more numerous fleet, with better-focused capabilities, to meet a range of scenarios in green and blue water environments" (Hughes, 2009, p. vii). Achieving a total of 677 ships within an affordable budget, it calls for a reduced emphasis on the expensive multi-mission warships of today, replacing some (but not all) with greater quantities of smaller, less expensive mission-focused ships, and puts more emphasis on "green water" (littoral or coastal) capabilities.

It is not the intent of this research to assess the potential efficacy of this new distributed and bimodal (featuring distinct littoral and open ocean elements) force. Nevertheless, we believe there are several reasons why the NNFM alternative is worthy of further analysis. First, having been designed from the ground up to meet the needs of *A Cooperative Strategy for 21st Century Sea Power* as interpreted though the considerable experience of the author and his collegues, it is exceptionally well suited to meeting those goals. By more than doubling the pool of available ships, requirements for additional forward presence and persistence of forces are clearly met. The need for "mission-tailored maritime forces" is addressed by an emphasis on increased mission specialization.

Second, very little is sacrificed in pursuit of these gains. A reasonable argument can be made that more ships are only better if they are the right ships—that the increased specialization that drives smaller ships and lower unit costs brings with it a reduced flexibility that simple numerical superiority might not overcome. While perhaps generally true, this is not the case in this instance. While down sized in tonnage, featuring destroyers and frigates (FFG) in place of the current mix of cruisers and destroyers, the NNFM plan actually achieves more multi-mission warships than the current OPNAV shipbuilding plan—a combined 120 DDG and FFG for the NNFM plan (Hughes, 2009, p. 50) as compared to the 88 DDG and CG in the current OPNAV plan (OPNAV N8F, 2010, p. 12). Carrier-based airpower faces a small reduction, with the NNFM concept calling for an end-strength of 620–680 aircraft vice the current 700 (Hughes, 2009, pp. 31–32). Increased future reliance on unmanned aerial vehicles may well render the real impact of this modest reduction moot.

Lastly, the NNFM plan is economically feasible. The proposed cost of $15 billion per year, though slightly higher than that of the current shipbuilding plan (Hughes, 2009, p. 11), is still smaller than the ship construction budget needed to achieve the Navy's proposed 313-ship program as outlined by OPNAV N8F (2010). In this age of tightening budget constraints, having a larger pool of less expensive construction projects is itself an asset. Cuts, when required, can be better tailored to meet specific savings goals. By having more construction "starts" to spread, the industrial base can be better preserved as well.

In summary, although our purpose in not to argue the case for the NNFM concept, it provides the capabilities to meet our future needs while maintaining our current core competencies. Moreover, it does so at an essentially equivalent cost to the current plan. It is better positioned to thrive with uncertain future budget limitations, and provides flexibility to better support the shipbuilding industrial base when needed. Additional second-order benefits exist, but we feel these reasons alone justify further exploration of the NNFM concept.

D. WHY WORRY ABOUT SUPPORTABILITY AT SEA?

In his introduction to Worrall Carter's *Beans, Bullets, and Black Oil*, Admiral Spruance writes: "A sound logistics plan is the foundation upon which a war operation should be based. If the necessary minimum of logistics support cannot be given to the combatant forces involved, the operation may fail, or at best be only partially successful" (Carter, 1953). This fundamental truth, that an "army travels on its stomach" (to quote Napoleon) has been understood, if not always heeded, since the time of Alexander the Great, if not earlier. Adequate logistical support is without a doubt a necessary condition for the success of any prolonged military campaign.

Admiral Henry Eccles further highlights that while naval logistics is the sum of many parts, the unparalleled "combination of power, flexibility and mobility" sea power offers will "remain potential rather than real unless the capabilities of mobile fleet support are fully developed and exploited" (Eccles, 1950, p. 97). In other words, replenishment at sea ("mobile fleet support") is a key enabler of many of the significant advantages that sea power affords, and as such plays a critical role in naval logistics strategy. As a crucial part of something that is well and long understood to be an important component of successful military campaigns, it is only right to ask "but can we support it at sea?"

The NNFM study leaves this as an open question. While acknowledging that a potential shortfall may exist, the current plan for 30 CLF ships is left unchanged with the provision that CLF force structure be "subjected to continuing review" as the "new fighting machine is constructed and deployed" (Hughes, 2009, p. 44). Given its focus on capabilities and archetypes over highly detailed platform specifications, this was a reasonable decision. Given the importance of supportability to successful operations, however, we feel it is never too early to begin thinking about questions of logistics now that the concepts and archetypes have been established.

Here are some clues that anticipate our conclusions. The last time the U.S. fleet approached the size of the proposed NNFM fleet in terms of number of ships was the 594-ship navy of 1987 (Naval Historical Center, 2011). At that time, estimates of the number of CLF ships required to support the fleet ranged from 65 to as many as 93 (CBO, 1988). At 677 ships, the NNFM features almost 15% more ships than the 1987 fleet of 594, and presently proposes to support it with only 30 CLF ships—at best half the number deemed necessary to support the smaller 1987 fleet. Clearly, supporting 15% more combatants with (at best) half of the number of CLF ships is a herculean task. While there have been advances in replenishment ship design over the past 25 years, the physical process of transferring materiel between ships at sea itself remains essentially unchanged and it is doubtful that the efficiencies gained to date are capable of covering such a massive shortfall.

II. METHODOLGY AND SCENARIO DESCRIPTION

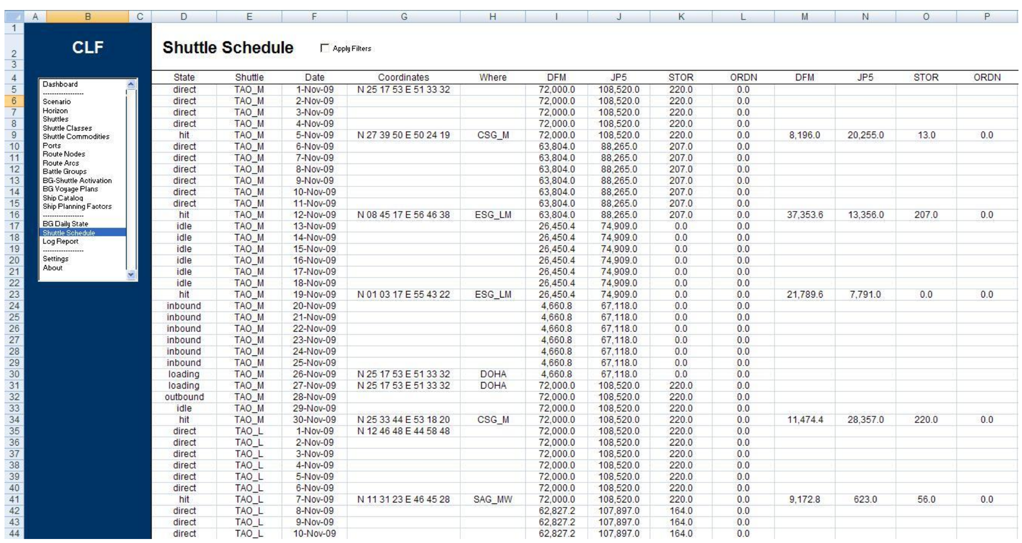
A. METHODOLOGY

The primary goal of this research is to provide an initial assessment of the ability of the current CLF to support a fleet of more numerous but smaller combatant ships like the one proposed in the NNFM study. As a secondary goal, we also seek to exercise the CLF Planner to demonstrate its flexibility for both force and campaign planning in a wide variety of circumstances. While other work has focused on adapting the underlying CLF Planner model to perform operational planning (Hallman, 2009), it is important to not lose sight of its origins as a strategic programmatic planning aid. With the CLF facing a pressing need to do more with less, Brown and Carlyle (2008, p. 800) set out to find a better way to "determine whether or not, and how, the new CLF can actually support its anticipated missions." Here, the problem has been inverted: instead of considering the impact of a changing CLF on the existing fleet, we are now concerned with the impact of a changing fleet on an existing CLF. We demonstrate that the CLF Planner is an excellent tool for performing such analysis.

To accomplish this, task groups of varying composition are run through a fixed employment scenario using the CLF Planner. Specifically, we first establish a baseline for performance by a force composed entirely of traditional (current) units. We then explore three variations to examine the impact of replacing various components of this traditional force with replacement platforms proposed by the NNFM. Day-by-day data are collected on task group inventory levels for each of the commodities tracked by the CLF Planner as well as CLF ship employment schedules. These data are then analyzed to roughly quantify any potential differences in support requirements and shortfalls in mission capacity that can be attributed to logistics. The source of our data for this analysis will be the daily battle group state (BG state) and CLF schedule worksheets generated by CLF Planner for each phase of the scenario.

A CLF schedule worksheet presents face-valid employment schedules for each of the CLF ships available that minimize customer shortfalls within the planning horizon

(Brown & Carlyle, 2008, p. 800). A sample of the output generated is shown as Figure 1. For every day in the planning horizon, each CLF ship is assigned to one of several possible employment states reflecting whether the ship in question is transiting to or from a given location ("inbound," "outbound," or "direct"), giving or receiving stores ("loading" and "consol"), or idle. While both the time available and the amount of each commodity held by the CLF ship in question are factors in whether or not a consolidation event can take place, time can always be traded for increased stores by returning to port for replenishment. Stores, however, cannot be easily traded for time. As such, *we choose to use time spent in idle status as a proxy for the latent support capacity that each CLF ship holds over the planning horizon in question.* To do so, we calculate a normalized idle rate for each CLF ship by dividing the number of days spent in "idle" status by the number of days in the planning horizon at hand. Although there are too many complicating factors to map this number directly to a amount of specific stores that could be delivered, insight can still be gained by using it comparatively.



State	Shuttle	Date	Coordinates	Where	DFM	JP5	STOR	ORDN	DFM	JP5	STOR	ORDN
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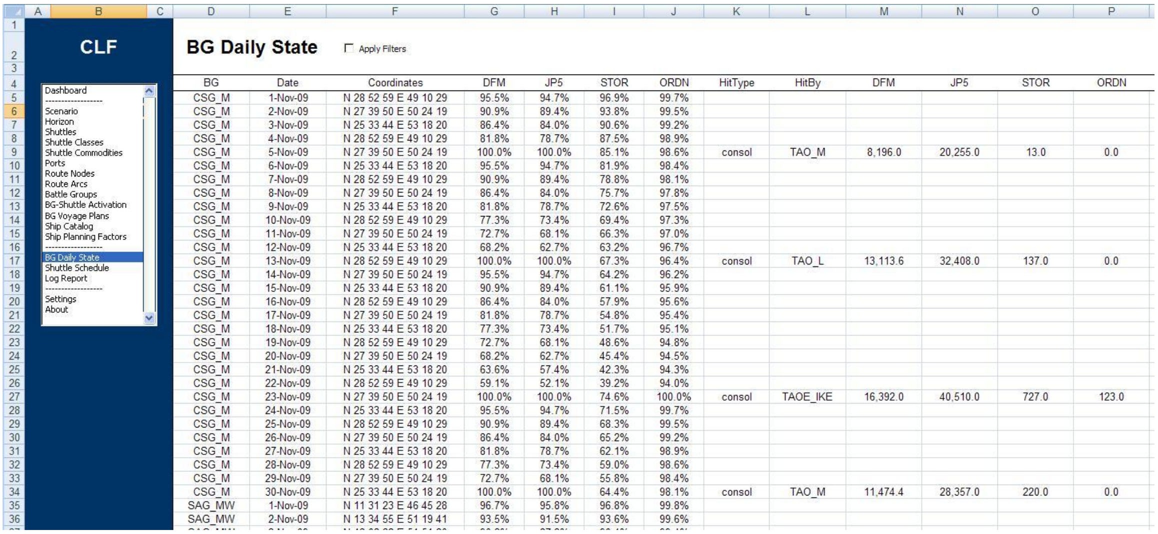
direct	TAO_M	2-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_M	3-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_M	4-Nov-09			72,000.0	108,520.0	220.0	0.0				
hit	TAO_M	5-Nov-09	N 27 39 50 E 50 24 19	CSG_M	72,000.0	108,520.0	220.0	0.0	8,196.0	20,255.0	13.0	0.0
direct	TAO_M	6-Nov-09			63,804.0	88,265.0	207.0	0.0				
direct	TAO_M	7-Nov-09			63,804.0	88,265.0	207.0	0.0				
direct	TAO_M	8-Nov-09			63,804.0	88,265.0	207.0	0.0				
direct	TAO_M	9-Nov-09			63,804.0	88,265.0	207.0	0.0				
direct	TAO_M	10-Nov-09			63,804.0	88,265.0	207.0	0.0				
direct	TAO_M	11-Nov-09			63,804.0	88,265.0	207.0	0.0				
hit	TAO_M	12-Nov-09	N 08 45 17 E 56 46 38	ESG_LM	63,804.0	88,265.0	207.0	0.0	37,353.6	13,356.0	207.0	0.0
idle	TAO_M	13-Nov-09			26,450.4	74,909.0	0.0	0.0				
idle	TAO_M	14-Nov-09			26,450.4	74,909.0	0.0	0.0				
idle	TAO_M	15-Nov-09			26,450.4	74,909.0	0.0	0.0				
idle	TAO_M	16-Nov-09			26,450.4	74,909.0	0.0	0.0				
idle	TAO_M	17-Nov-09			26,450.4	74,909.0	0.0	0.0				
idle	TAO_M	18-Nov-09			26,450.4	74,909.0	0.0	0.0				
hit	TAO_M	19-Nov-09	N 01 03 17 E 55 43 22	ESG_LM	26,450.4	74,909.0	0.0	0.0	21,789.6	7,791.0	0.0	0.0
inbound	TAO_M	20-Nov-09			4,660.8	67,118.0	0.0	0.0				
inbound	TAO_M	21-Nov-09			4,660.8	67,118.0	0.0	0.0				
inbound	TAO_M	22-Nov-09			4,660.8	67,118.0	0.0	0.0				
inbound	TAO_M	23-Nov-09			4,660.8	67,118.0	0.0	0.0				
inbound	TAO_M	24-Nov-09			4,660.8	67,118.0	0.0	0.0				
inbound	TAO_M	25-Nov-09			4,660.8	67,118.0	0.0	0.0				
loading	TAO_M	26-Nov-09	N 25 17 53 E 51 33 32	DOHA	4,660.8	67,118.0	0.0	0.0				
loading	TAO_M	27-Nov-09	N 25 17 53 E 51 33 32	DOHA	72,000.0	108,520.0	220.0	0.0				
outbound	TAO_M	28-Nov-09			72,000.0	108,520.0	220.0	0.0				
idle	TAO_M	29-Nov-09			72,000.0	108,520.0	220.0	0.0				
hit	TAO_M	30-Nov-09	N 25 33 44 E 53 18 20	CSG_M	72,000.0	108,520.0	220.0	0.0	11,474.4	28,357.0	220.0	0.0
direct	TAO_L	1-Nov-09	N 12 46 48 E 44 58 48		72,000.0	108,520.0	220.0	0.0				
direct	TAO_L	2-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_L	3-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_L	4-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_L	5-Nov-09			72,000.0	108,520.0	220.0	0.0				
direct	TAO_L	6-Nov-09			72,000.0	108,520.0	220.0	0.0				
hit	TAO_L	7-Nov-09	N 11 31 23 E 46 45 28	SAG_MW	72,000.0	108,520.0	220.0	0.0	9,172.8	623.0	56.0	0.0
direct	TAO_L	8-Nov-09			62,827.2	107,897.0	164.0	0.0				
direct	TAO_L	9-Nov-09			62,827.2	107,897.0	164.0	0.0				
direct	TAO_L	10-Nov-09			62,827.2	107,897.0	164.0	0.0				

Figure 1. Sample CLF planner schedule. On the left is the control panel used to access the reports and data entry pages. Shuttle schedule information is in the table on the right. Each line in the table describes the activity of one specific shuttle on one specific day of the scenario. Entries within each line include (from left to right) employment status of the shuttle for that day, shuttle identification label, scenario day, geographic location, client ship serviced that day (if any), quantity of commodities available for transfer at the end of day, and quantity of commodities transferred that day (if any).

The BG state worksheet provides a day-by-day accounting of the projected percentage of capacity held by each task group for each of the four commodity groups tracked by CLF Planner given the specified operational tasking of that task group and the generated replenishment schedule. An example of this report is shown as Figure 2. From this data, we construct additional data points representing *what portion of the planning horizon each task group spends below the danger (50%) and extremis (25%) inventory thresholds*. These serve as our proxy for mission capability. A ship in a danger status may be able to complete assigned tasking, but will lack flexibility compared to a ship with ample stores when reality inevitably begins to diverge from our simplified model. Ships that reach extremis levels would be unable to prosecute mission tasking at all, being forced instead to actively pursue replenishment before becoming a casualty. As with CLF idle rates, these metrics are intended to be used comparatively. So long as on-hand balances remain strictly positive, higher danger and idle rates do not necessarily mean that a task group will fail to perform its assigned tasks. Instead, we consider only that when comparing two task groups the group with lower danger and idle rates would have greater operational flexibility and that, all other things being equal, this flexibility is highly desirable.



BG	Date	Coordinates	DFM	JP5	STOR	ORDN	HitType	HitBy	DFM	JP5	STOR	ORDN
CSG_M	1-Nov-09	N 28 52 59 E 49 10 29	95.5%	94.7%	96.9%	99.7%						
CSG_M	2-Nov-09	N 27 39 50 E 50 24 19	90.9%	89.4%	93.8%	99.5%						
CSG_M	3-Nov-09	N 25 33 44 E 53 18 20	86.4%	84.0%	90.6%	99.2%						
CSG_M	4-Nov-09	N 28 52 59 E 49 10 29	81.8%	78.7%	87.5%	98.9%						
CSG_M	5-Nov-09	N 27 39 50 E 50 24 19	100.0%	100.0%	85.1%	98.6%	consol	TAO_M	8,196.0	20,255.0	13.0	0.0
CSG_M	6-Nov-09	N 25 33 44 E 53 18 20	95.5%	94.7%	81.9%	98.4%						
CSG_M	7-Nov-09	N 28 52 59 E 49 10 29	90.9%	89.4%	78.8%	98.1%						
CSG_M	8-Nov-09	N 27 39 50 E 50 24 19	86.4%	84.0%	75.7%	97.8%						
CSG_M	9-Nov-09	N 25 33 44 E 53 18 20	81.8%	78.7%	72.6%	97.5%						
CSG_M	10-Nov-09	N 28 52 59 E 49 10 29	77.3%	73.4%	69.4%	97.3%						
CSG_M	11-Nov-09	N 27 39 50 E 50 24 19	72.7%	68.1%	66.3%	97.0%						
CSG_M	12-Nov-09	N 25 33 44 E 53 18 20	68.2%	62.7%	63.2%	96.7%						
CSG_M	13-Nov-09	N 28 52 59 E 49 10 29	100.0%	100.0%	67.3%	96.4%	consol	TAO_L	13,113.6	32,408.0	137.0	0.0
CSG_M	14-Nov-09	N 27 39 50 E 50 24 19	95.5%	94.7%	64.2%	96.2%						
CSG_M	15-Nov-09	N 25 33 44 E 53 18 20	90.9%	89.4%	61.1%	95.9%						
CSG_M	16-Nov-09	N 28 52 59 E 49 10 29	86.4%	84.0%	57.9%	95.6%						
CSG_M	17-Nov-09	N 27 39 50 E 50 24 19	81.8%	78.7%	54.8%	95.4%						
CSG_M	18-Nov-09	N 25 33 44 E 53 18 20	77.3%	73.4%	51.7%	95.1%						
CSG_M	19-Nov-09	N 28 52 59 E 49 10 29	72.7%	68.1%	48.6%	94.8%						
CSG_M	20-Nov-09	N 27 39 50 E 50 24 19	68.2%	62.7%	45.4%	94.5%						
CSG_M	21-Nov-09	N 25 33 44 E 53 18 20	63.6%	57.4%	42.3%	94.3%						
CSG_M	22-Nov-09	N 28 52 59 E 49 10 29	59.1%	52.1%	39.2%	94.0%						
CSG_M	23-Nov-09	N 27 39 50 E 50 24 19	100.0%	100.0%	74.6%	100.0%	consol	TAOE_IKE	16,392.0	40,510.0	727.0	123.0
CSG_M	24-Nov-09	N 25 33 44 E 53 18 20	95.5%	94.7%	71.5%	99.7%						
CSG_M	25-Nov-09	N 28 52 59 E 49 10 29	90.9%	89.4%	68.3%	99.5%						
CSG_M	26-Nov-09	N 27 39 50 E 50 24 19	86.4%	84.0%	65.2%	99.2%						
CSG_M	27-Nov-09	N 25 33 44 E 53 18 20	81.8%	78.7%	62.1%	98.9%						
CSG_M	28-Nov-09	N 28 52 59 E 49 10 29	77.3%	73.4%	59.0%	98.6%						
CSG_M	29-Nov-09	N 27 39 50 E 50 24 19	72.7%	68.1%	55.8%	98.4%						
CSG_M	30-Nov-09	N 25 33 44 E 53 18 20	100.0%	100.0%	64.4%	98.1%	consol	TAO_M	11,474.4	28,357.0	220.0	0.0
SAG_MW	1-Nov-09	N 11 31 23 E 46 45 28	96.7%	95.8%	96.8%	99.8%						
SAG_MW	2-Nov-09	N 13 34 55 E 51 19 41	93.5%	91.5%	93.6%	99.6%						

Figure 2. Sample BG state report. On the left is the control panel used to access the reports and data entry pages. Daily task group state information is in the table on the right. Each line represents the state of the specified task group on the specified day. Entries within each line include (from left to right) the task group label, scenario day, geographic coordinates, end of day on-hand commodity balances as a percentage of capacity, in indicator of type of replenishment conducted (if any), the shuttle providing commodities (if any), and the amount (in abstract *c*-units) of each commodity received that day, if any.

B. SCENARIO DESCRIPTION

The scenario employed focuses on two carrier strike groups (CSG), denoted as SDCA_CSG and MED_CSG based on their starting positions, involved in a major conflict in the South China Sea. Although an actual major theater conflict would be conducted with far more than this, two CSG are key components to conduct the sustained high-tempo round-the-clock flight operations required and represent a sensible building block with which to start. The scenario is 100 days in total length and consists of three phases that cover a wide range of operational employment tempos. Although the conflict is set in the South China Sea for modeling purposes, the geography involved is easily generalized. The key characteristics are two CSGs within 800 nm of each other with at least one port available for replenishment within approximately 1000 nm, as depicted in Figure 3.

Figure 3. Scenario geography. The star indicates the position of the forward logistics hub in Singapore. The two triangles represent the centers of the two task group operating areas. The shaded circle indicates a 1000nm radius from Singapore. Map from the CIA World Fact Book (CIA, 2012).

The scenario is broken into three phases. Timelines and tasking for each phase are derived from a series of unpublished analyses conducted as part of a resident Joint Campaign Analysis course at the Naval Postgraduate School. As part of this course, the broad question of how to conduct an opposed amphibious landing in the South China Sea was examined in five domains, with each assigned a team of Operations Research and Systems Engineering students to perform analysis of the requirements and likely outcomes of the conflict within their domains. Two of these are directly pertinent to the development of the scenario explored here. Alexander, Dozier, and Nevo (2011) explore the needs and timelines of a successful air superiority campaign. Chiam, Geiser, and Jensen (2011) consider the requirements for a successful maritime superiority and anti-submarine warfare campaign.

Previous work produced in this forum on the Falkland Islands and Desert Storm conflicts was found to be similar enough to the events as they eventually unfolded to be highly useful for planning. Therefore, we feel comfortable that the scenario is at least a reasonable approximation of the requirements of an actual conflict for a rough order of magnitude analysis such as this.

Each phase of the scenario is modeled independently to facilitate tailoring the support assets available to the demands of the operation. This cascading solves approach has the added benefit of reducing the size, and therefore solve time, of the resulting mixed integer program (MIP). To manage the transitions between phases, task group inventory state at the end of each planning window is carried forward to become the starting state for the next phase. CLF ships that end a phase in an idle state at less than full capacity are manually repositioned to the closest replenishment point and become available fully loaded in the next phase after an appropriate delay to account for transit and reloading times. CLF Planner is allowed to optimally position those CLF ships that end the previous phase idle and loaded, and those CLF ships that end a phase with a consolidation event are left as they were at the end of the phase.

The first phase modeled is the "Transit" one, where the two task groups transit from their starting positions to the assigned operating area. This phase spans 17 days, with both task groups assigned to the "InTransit" employment category within CLF Planner throughout. This requires moderate DFM and JP5 usage but very low ordnance consumption and exemplifies the demands of high-speed transit with limited resupply opportunities due to the high speed of advance required of the task groups.

The second ("Assault") phase consists of 38 days of high intensity combat operations with both task groups assigned to the "Assault" employment category throughout, driving high levels of demand for all commodities. This phase models the major combat operations required to achieve air and maritime superiority within the region. In reality, the strain of conducting 38 consecutive days of maximum-tempo flight operations may prove too much for the warships and their crews to handle and actual consumption might be somewhat less. Deriving an appropriate ratio of maximum effort to recovery days, however, is beyond the scope of this research and as such, we err on the side of caution and assume the maximal level of demand for the entire 38-day period.

The final ("Sustain") phase of the operation lasts 45 days. During this phase, task groups are assigned within CLF Planner to 21 days of "Sustain" operations followed by 24 days of "OnStation." This combination drives moderately high levels of demand for fuel but substantially less ordnance requirements. It is intended to represent the level of effort required to maintain air and maritime superiority that has already been established. In more general application, this would be similar to the level of effort required by a low-to-mid-intensity conflict within an AOR in which U.S. superiority was not directly challenged.

With the scenario laid out into manageable pieces, one additional challenge needs to be addressed. As events in both the Atlantic and Pacific Oceans during the second World War have shown, the long supply lines required to support a major overseas war present an attractive target to a capable naval adversary. To counter this threat, we must consider the need to protect our CLF ships. Barring significant "hardening" of U.S. CLF ships, this will require the assignment of additional combatants in an escort role. Because CLF Planner generates CLF voyage plans in response to the fixed combatant voyage plans provided at run time we cannot simply assign surface combatants to escort each CLF ship. Still, we point out that the additional logistical demand posed by the escort ships could prove significant and must be accounted for. For modeling purposes, our solution to this problem is to decrease the capacities of each CLF unit by an amount equal to 14 days consumption by a DDG operating in an "InTransit" status. In running the model throughout the course of the research, this 14 days proved to be a very conservative upper bound for the amount of time a CLF ship might spend between port calls, validating this figure as a reasonable safety buffer.

C. LITERATURE REVIEW

The application of the techniques of optimization to the problems of naval logistics is far from new, dating back to at least the 1950s (see references of Brown & Carlyle, 2008). CLF Planner, the underlying model used in our analysis, is itself the product of a long series of NPS theses. Borden (2001) laid the foundation for much of what was to become CLF Planner in his exploration of the (at the time) proposed T-AKE platform. Givens (2002) introduces the ability to restrict shuttle access to ports, significantly improving solve times for theater-based (vice worldwide) scenarios. Lastly, Doyle (2006) consolidated the incremental improvements proposed by Cardillo (2004) and DeGrange (2005), as well as adding provisions for numbered fleet ownership of CLF assets.

This research differentiates itself from these past efforts in its attempt to move beyond calculating the minimum number of CLF ships required to support a particular fleet under a particular set of business rules into quantifying (however roughly) what that minimum level of support actually "buys" in terms of potential mission flexibility and unused support capacity. It is our hope that these insights will encourage future combatant and support fleets to be developed synchronously, to the benefit of both.

III. INTRODUCTION TO THE COMBAT LOGISTICS FORCE (CLF) PLANNER

A. DESCRIPTION AND HISTORY

The CLF Planner, canonically described by Brown and Carlyle (2008), is an integer linear optimization model that seeks to maximize the distribution of multiple commodities to clients (combatant ships) by providers (replenishment ships). Moving beyond a simple tanker-scheduling problem, it considers both geographic constraints and the escalating impact of allowing client commodity levels to fall too low. Because potential commodity transfers are constrained by the geography of the scenario—time, distance, and navigability of intermediary sea routes are all considered—it does not overestimate the efficiency of the CLF as many steady-state analyses do (DeGrange, 2005). Because it uses an optimization model, the analyst can rest assured that the solutions returned accurately represent the very best level of support that can be achieved within the scenario as described. Additionally, all significant model parameters are user adjustable, with input and output coordinated via an Excel (Microsoft, 2007) spreadsheet front end. These three traits make it an attractive and powerful tool for performing analysis such as that undertaken here.

Within CLF Planner, the commodities typically replenished at sea are categorized into four groups: marine diesel fuel (DFM); aviation fuel (JP5); stores (STORES), which includes both foodstuffs and general supplies; and ordnance (ORDN). Within the model, specific units of measure are abstracted away by the use of a generalized unit of measure called a "*c-unit.*" For reference, the capacities and consumption rates within the model are based on the logistics planning factors found in NWP 4.01-2 (CNO NWP 4-01.2, 2007), and translate as barrels (42 U.S. gallons) for DFM and JP5 and short tons (2,000 pounds) for STORES and ORDN.

Client (combatant) ships are defined by class—e.g., destroyer (DDG), cruiser (CG), or frigate (FFG). For every commodity group in the model, each ship class has a capacity and a set of daily consumption rates based on the operational employment of the client. Operational employment categories can be user-defined, with a robust set based on NWP 4.01-2 built into the model by default.

Combatant ships are organized into task groups for voyage planning purposes. Brown and Carlyle (2008) refer to any such set of combatant ships as a "battle group" (BG). Since the phrase "battle group" carries connotations of a particular force structure, we choose to adopt the more general "task group" in its place, but the two terms are intended to be used interchangeably. The voyage plan specifies a geographic position and operational employment category for the task group on each day in the planning horizon under consideration.

Replenishment (CLF) ships, or shuttles, are defined by a separate set of parameters that include their top sustained speed and capacities for each commodity group. Definitions are included for each class of replenishment ship currently in the U.S. inventory, including several potential configurations for the multi-commodity T-AKE. A handful of Canadian and United Kingdom oilers are included as well. If further flexibility is desired, the planner may specify additional classes of either combatant or replenishment ships.

Solutions are generated in two steps. First, feasible shuttle tracks are created by overlaying the specified task group voyage plans on top of an internal global sea routes network (illustrated in Figure 4). Nodes are added at each intersection between voyage plan and sea route network arc to enable shuttles to transit along combatant voyage plan tracks as needed. The resulting composite network is used to generate the minimum travel time (in days) between all pairs of nodes for each shuttle. These travel times are then used to generate a data set describing the time required for each shuttle to meet task group x on day dx, return to port, then meet task group y on day dy. This second data set allows the second phase of the solution to quickly discard shuttle employment schedules that are geographically infeasible.

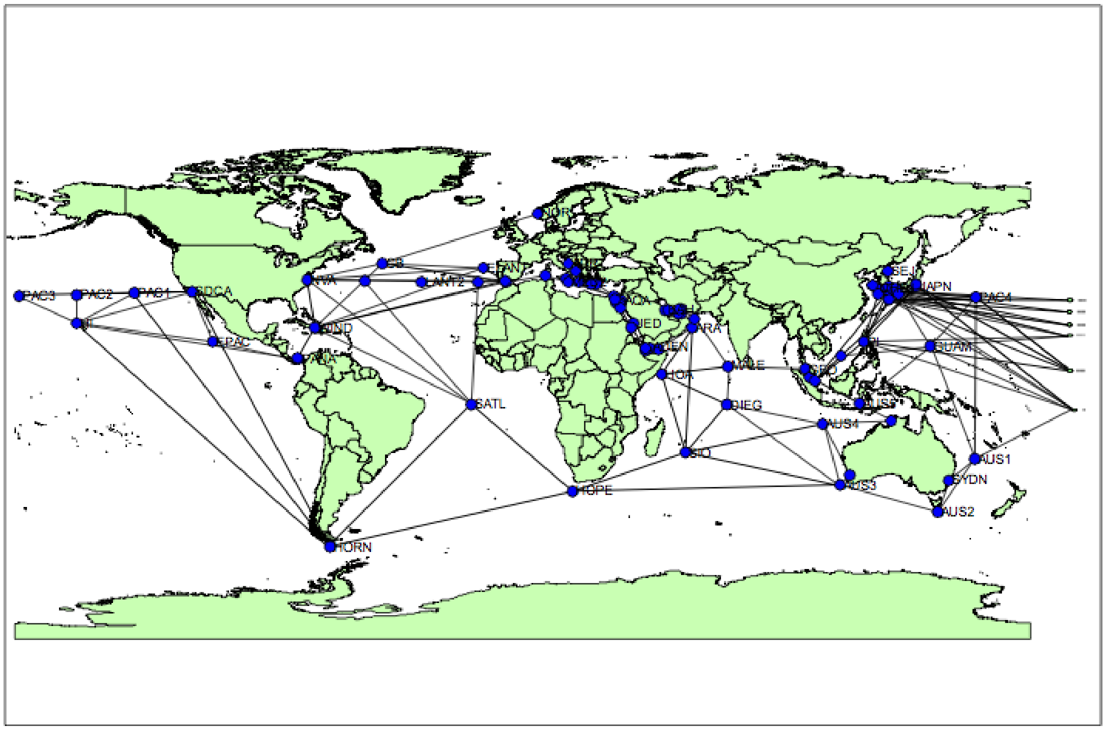


Figure 4. Illustration of global sea routes network.
(From DeGrange, 2005)

The second phase of solution is the actual mixed integer program (MIP) itself. The objective of this program is to maximize shuttle throughput by choosing the set of replenishment events that moves the most materiel from shuttles to combatants. The total volume delivered for each commodity group is rewarded on a per-unit-delivered basis. Each commodity group is individually weighted, and weights can be adjusted to allow for differences in the scale of *c*-units and to influence model behavior—to prioritize the delivery of fuel over food, for instance. To ensure that all task groups are serviced, a series of escalating penalties is applied to solutions that allow task groups to fall below user-specified “danger” and “extremis” thresholds. Penalties are assessed on a unit of deficiency per day basis, and therefore accumulate quickly. Penalties are expressed as a multiple of the reward received for the delivery of that commodity. For example, by default delivering one unit of DFM is worth one “point” of objective function value, while each day of shortage carries a penalty of ten “points” per unit of deficiency for violating the danger threshold and 100 “points” per unit of deficiency in violation of the extremis threshold. To maximize the size of the feasible solution region, negative balances are permissible but carry an even more prohibitively heavy penalty. This second stage MIP is constrained by both the geographic factors determined in the first stage as well as logistical factors such as inventory balances and limits on the number of consolidation events that any ship can conduct in a given day.

The first output of this second stage is the set of replenishment events that deliver the maximum amount of commodities while incurring the minimum penalties for allowing individual task groups to violate the danger and extremis thresholds. Because scenario geography is included as a constraint for the MIP, this set of events represents a face-valid replenishment plan for the scenario as described in the model. This plan is translated into two primary outputs. The first is a set of voyage plans for each CLF ship. These outline the daily position and activity of each CLF ship in much the same way as the combatant voyage plans do. Utilizing both sets of voyage plans, the Excel interface is able to generate an animated visualization of the activities of all ships as one moves through the planning horizon.

The second output is a listing of daily commodity states for each task group. Using combatant capacities and consumption planning factors, on-hand balances for each commodity group are calculated for each task group for every day in the planning horizon. To aid in visualization, the Excel interface is capable of generating a “sawtooth” chart showing the on-hand balance for a specified commodity group for any combatant unit (or units) of interest. Figure 5 depicts what a typical sawtooth chart might look like.

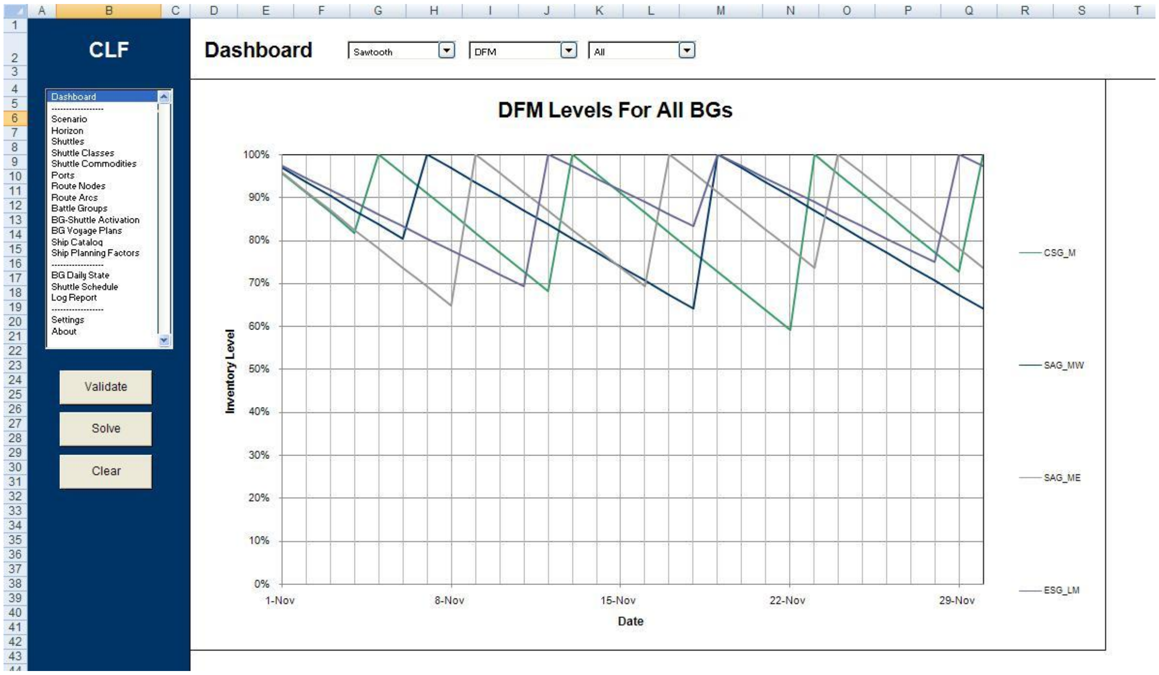


Figure 5. Sample sawtooth chart. Here, daily DFM balances are shown for four different task groups over the course of 30 days. Peaks represent completed replenishment events and the slope of the line indicates the rate of consumption.

B. FORMULATION

For completeness, the formulation from Brown and Carlyle (2008) follows. The few refinements we propose were implemented outside of the MIP itself. A summary of the canonical formulation is provided here for reference.

1. Indices [~ cardinality]

$s \in S$ Shuttle ship [~7]

$p \in P$ Ports available for loading shuttle ships [~5]

$bg \in BG$ Battle group [~2] (aliased as bx,by)

$d \in D$ Day [~100] (aliased as dx, dy, dh)

$c \in C$ Commodity group (DFM, JP5, STOR, ORDN) [~4]

$\hat{c} \subseteq C$ Dry commodity subject to load fraction restrictions (STOR, ORDN)

2. Provided Data [units]

$spdSHUTTLE_s$ Speed of shuttle ship *s* [nm/day]

$inptTAT$ Time to reload shuttle ship in port [days]

$portok4s_{s,p}$ Binary indicator that shuttle *s* can reload at port *p*

$legdays_{s,bg,d,p}$ Transit time for shuttle *s* from battle group *bg* position on day *d* to port *p* following established sea routes and/or BG tracks [days]

$useBG_{bg,d,c}$ Consumption of commodity *c* by *bg* on day *d* [c-units]

$mxload_{bg,c}$ Maximum capacity of *bg* for commodity *c* [c-units]

$safety_c$ Minimum desired fraction of $mxload_{bg,c}$ to be held at all times [fraction]

$extremis_c$ Extreme minimum desired fraction of $mxload_{bg,c}$ to be held at all times [fraction]

$hitOK_{bg,d}$ Binary indicator that *bg* can receive stores on day *d* [binary]

$capacity_{s,c}$ Capacity of shuttle *s* for commodity *c* [c-units]

$mnfrac_{\hat{c}}, mxfrac_{\hat{c}}$ Minimum, maximum fraction of T-AKE dry capacity that must be loaded with dry commodity $\hat{c}$ [fraction]

$safety\_penalty_c$ Penalty per unit of deficit below desired safety stock level for commodity *c* by any battle group [penalty per c-unit]

$extremis\_factor$ Multiplier (>1, default is 10) for penalty per unit of deficit below desired extremis level for commodity *c* by any battle group [dimensionless]

$negative\_factor$ Multiplier (>*extremis_factor*, default is 1000) for penalty per unit of deficit below zero for commodity *c* by any battle group [dimensionless]

3. Derived Data

$mxconsol_{s,bg,c}$ Maximum quantity of commodity *c* [in *c*-units] that shuttle *s* can deliver to *bg* on any given day. Defined as $\min\left\{mxload_{bg,c}, capacity_{s,c}\right\}$.

$mxconsol2_{s,bg,bx,c}$ Maximum quantity of commodity *c* [in *c*-units] that shuttle *s* can deliver to task groups *bg* and *bx* when conducting two CONSOL events during a single excursion from port. Defined as $\min\{mxload_{bg,c} + mxload_{bx,c}, capacity_{s,c}\}$.

$directdays_{s,bg,d,bx,dx}$ Transit time [days] required for shuttle *s* to transit from the position of *bg* on day *d* directly to the position of *bx* on day *dx* without intermediary stops (i.e., visiting port to replenish bunker stores).

4. Decision Variables

$HIT_{s,bg,d}$ Binary indicator of shuttle *s* conducting a CONSOL event with *bg* on day *d*.

$HIT2_{s,bg,d,bx,dx}$ Binary indicator of shuttle *s* conducting a CONSOL event with *bg* on day *d*, followed by a second CONSOL event with *bx* on day *dx* before returning to port.

$CONSOL_{s,bg,d,c}$ Amount of commodity *c* [in *c*-units] delivered by shuttle *s* to *bg* on day *d*.

$CONSOL12_{s,bg,d,bx,dx,c}$
$CONSOL22_{s,bg,d,bx,dx,c}$ Amount of commodity *c* [in *c*-units] delivered by shuttle *s* to *bg* on day *d* and *bx* on day *dx* (respectively) when conducting multiple CONSOL events before returning to port.

$SHORTAGE_{bg,d,c}$ Amount of deficiency below danger threshold in commodity *c* [in *c*-units] for *bg* at the end of day *d*.

$EXTREMIS_{bg,d,c}$ Amount of deficiency below extremis threshold in commodity *c* [in *c*-units] for *bg* at the end of day *d*.

$NEGINV_{bg,d,c}$ Magnitude of negative inventory balance in commodity *c* [in *c*-units] for *bg* at the end of day *d*.

5. Formulation

$$\begin{aligned}
&\underset{\substack{HIT,HIT2,CONSOL,CONSOL12,CONSOL22,\\ SHORTAGE,EXTREMIS,NEGINV}}{MIN} \sum_{s,bg,d,c} -0.1 safety_penalty_c * CONSOL_{s,bg,d,c} \\
&+ \sum_{\substack{s,bg,d,bx,\\ dx|dx-d \geq directdays_{s,bg,d,bx,dx}}} -0.1 safety_penalty_c * (CONSOL12_{s,bg,d,bx,dx,c} + CONSOL22_{s,bg,d,bx,dx,c}) \\
&+ \sum_{bg,d,c} safety_penalty_c * SHORTAGE_{bg,d,c} \\
&+ \sum_{bg,d,c} extremis_factor * safety_penalty_c * EXTREMIS_{bg,d,c} \\
&+ \sum_{bg,d,c} negative_factor * safety_penalty_c * NEGINV_{bg,d,c}
\end{aligned} \tag{1}$$

Subject to:

$$\begin{aligned}
&\sum_{s,dh \leq d} CONSOL12_{s,bg,dh,c} + \sum_{s,dh \leq d,bx,dx} CONSOL12_{s,bg,dh,bx,dx,c} \\
&+ \sum_{s,dh \leq d,bx,dx} CONSOL22_{s,bx,dx,bg,dh,c} \leq \sum_{dh \leq d} useBG_{bg,dh,c} \quad \forall\, bg,d,c
\end{aligned} \tag{2}$$

$$\sum_{s,dh \le d} CONSOL_{s,bg,dh,c} + \sum_{s,dh \le d,bx,dx} CONSOL12_{s,bg,dh,bx,dx,c}$$
$$+ \sum_{s,dh \le d,bx,dx} CONSOL22_{s,bg,dh,bx,dx,c} + SHORTAGE_{bg,d,c} + EXTREMIS_{bg,d,c}$$
$$+ NEGINV_{bg,d,c} \le \sum_{dh \le d} useBG_{bg,dh,c} - (1 - safety_c) * mxload_{bg,c} \quad \forall\ bg,d,c \tag{3}$$

$$CONSOL_{s,bg,d,c} \le mxconsol_{s,bg,c} * HIT_{s,bg,d} \quad \forall\ s,bg,d,c \tag{4}$$

$$CONSOL12_{s,bg,d,bx,dx,c} + CONSOL22_{s,bg,d,bx,dx,c}$$
$$\le mxconsol2_{s,bg,bx,c} * HIT2_{s,bg,d,bx,dx} \quad \forall\ s,bg,d,bx,dx,c \tag{5}$$

$$HIT_{s,bd,d} + \sum_{\substack{by,dy| \\ d-dy \ge directdays_{s,by,dy,bg,d}}} HIT2_{s,by,dy,bg,d} + HIT_{s,bx,dx}$$
$$+ \sum_{\substack{by,dy| \\ dy-dx \ge directdays_{s,bx,dx,by,dy}}} HIT2_{s,bx,dx,by,dy} \le 1 \quad \forall s,bg,d,bx,dx \mid dx - d < cycledays_{s,bg,d,bx,dx} \tag{6}$$

$$\sum_{bg} HIT_{s,bg,d} + \sum_{bx,by,dx \le d \le dy} HIT2_{s,bx,dx,by,dy} \le 1 \quad \forall\ s,d \tag{7}$$

$$HIT_{s,bg,d} \in \{0,1\} \quad \forall\ s,bg,d \tag{8}$$

$$HIT2_{s,bg,d,bx,dx} \in \{0,1\} \quad \forall\ s,g,d,bx,dx \tag{9}$$

$$0 \le CONSOL_{s,bg,d,c} \le mxconsol_{s,bg,c} \quad \forall\ s,bg,d,c \tag{10}$$

$$0 \le CONSOL12_{s,bg,d,bx,dx,c} \le mxconsol_{s,bg,c} \quad \forall\ s,bg,d,bx,dx,c \tag{11}$$

$$0 \le CONSOL22_{s,bg,d,bx,dx,c} \le mxconsol_{s,bx,c} \quad \forall\ s,bg,d,bx,dx,c \tag{12}$$

$$0 \le SHORTAGE_{bg,d,c} \le (safety_c - extremis_c) * mxload_{bg,c} \quad \forall\ bg,d,c \tag{13}$$

$$0 \le EXTREMIS_{bg,d,c} \le extremis_c * mxload_{bg,c} \quad \forall\ bg,d,c \tag{14}$$

$$0 \le NEGINV_{bg,d,c} \quad \forall\ bg,d,c \tag{15}$$

6. Discussion

The objective function (1) rewards the volume of commodities delivered, then assesses escalating penalties for shortages below the safety, extremis and zero stock on hand (negative inventory balances) levels. To encourage maximal delivery volumes, deliveries are rewarded at a rate of ten percent of the safety stock level shortage penalty. A lower rate (i.e., rewarding deliveries at a rate of one percent) encourages deliveries that only avoid shortages, while a higher rate mutes the effect of the shortage penalties. Note that the relative importance of each commodity group within the scenario can be adjusted by changing the associated shortage penalty.

Inequalities (2) limit the total cumulative volumes of commodities delivered to each task group to the cumulative usage of that task group through the end of that day. It is assumed that every task group is at capacity in every commodity on the first day. Limiting total deliveries to total consumption to date serves to prevent task groups from being "overfilled." Elastic inequalities (3) compare total volumes received to total volumes consumed in each commodity for each task group, assigning shortages (if any) to the appropriate category as necessary to achieve balance.

Inequalities (4) and (5) ensure that commodities can only be transferred between a shuttle and task group on days for which a consolidation event has been scheduled. Inequalities (4) govern the single consolidation event case, while inequalities (5) govern the case where two events are scheduled between shuttle port visits. Constraint (6) ensures that adequate time is available between successive consolidation events for each shuttle to return to port and reload. Constraint (7) limits each shuttle to a maximum of one consolidation event per day. Equations (8)–(15) provide variable domain constraints.

C. EXTENSIONS TO THE MODEL

Our first extension to the model makes a provision for the inclusion of an armed escort for each of our CLF ships. Our scenario, discussed in more depth in Chapter II, models a wartime engagement. During such a conflict, it is reasonable to assume that our logistics chain might come under attack by a capable enemy and must therefore be defended. Because CLF voyage plans are unknown prior to solution generation, it is not possible to simply add combatant units to explicitly escort CLF ships as part of the voyage planning process. Because CLF Planner is such a flexible and robust tool, however, we were able to implement a solution to this problem without making changes to the underlying formulation of the model. Starting with the assumption that escort ships would be serviced by their assigned CLF ship on an “as-needed” basis, our solution is to model escorts implicitly by reducing the bunker capacity of our CLF forces. In essence, we require each CLF ship to maintain a safety buffer to support its assigned escort. Rather than increasing the complexity of the model by adding additional constraints, we achieve the same effect by simply adjusting the model parameters at the outset.

Our second addition to the model addresses the tedious and time-consuming task of generating task group voyage plans. Toward this end, a simple utility was written in Java (Oracle Corp., 2012). This utility requires three simple inputs: the starting and ending positions of the desired movement and an average transit speed. From these inputs, it will generate a listing of end-of-day positions that can be used to populate a voyage plan within the CLF Planner. In addition to computing daily travel distances and positions in accordance with the principles of great-circle navigation, the tool has the added benefit of generating tracks that fall along the existing CLF Planner global sea routes network. By laying our combatant tracks on top of the default CLF tracks, we ensure ample opportunities for replenishments to occur.

The operation of this tool is simple. First, it locates the closest nodes to the specified endpoints on the global sea routes network built into CLF Planner. Dykstra’s algorithm (e.g., Ahuja, Magnanti & Orlin, 1993, p. 108ff) is then used to find the shortest path between those nodes. The starting and ending nodes of this shortest path are then replaced with the specified starting and ending positions to prevent backtracking in those cases where an endpoint falls in between nodes along the generated path. The provided transit speed is used to compute the total distance the task group can travel in 24 hours, and the shortest path is broken into segments of this length the determine end-of-day positions. As the majority of these will fall in between the established nodes of the original sea routes network, care is taken to calculate these intermediate positions along a proper great-circle arc between the starting and ending nodes. The results of this utility offer a good approximation of a feasible track quickly and with minimal work on the part of the planner. We found it to be quite useful.

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IV. ANALYSIS AND RESULTS

A. ESTABLISHING A BASELINE FOR PERFORMANCE AND SUPPORT

Before considering the impact of any shift in force composition, we must first establish a baseline for comparison. In this case, we seek to establish the minimum feasible support requirements necessary for a traditional force to complete the assigned scenario. "Minimum feasible support requirements" is defined as the smallest set of CLF ships needed to maintain strictly positive commodity balances on hand throughout the duration of the scenario. Excursions below the danger and extremis thresholds of 50 and 25 percent are permissible as combatant units would still be able to execute assigned tasking. Negative balances, however, would translate to unit casualties—literally so, if the commodities in question are food or fuel.

The combatant forces to be supported in our baseline scenario are two CVN-based Carrier Strike Groups (CSG), each composed of one traditional Nimitz-class CVN, two cruiser class escorts and two destroyer class escorts. The first CSG (denoted MED_CSG) begins the scenario in the Mediterranean Sea, transits the Suez Canal, and takes station at N 5.0° E 107.5°, roughly 315 nm away from the replenishment hub. The second CSG (denoted SDCA_CSG) begins the scenario in San Diego, California, and, after a short delay to ensure synchronized arrival with MED_CSG, proceeds directly to take station at N 5.0° E 120.0°, roughly 1,000 nm away from the replenishment hub. The daily commodity consumption rates by phase for the two CSGs are tabulated for comparison to future alternate force mixes and are summarized in Table 1. All values are in *c*-units.

	Transit Phase			Assault Phase			Sustain Phase		
Commodity	MED_ CSG	SDCA_ CSG	Total	MED_ CSG	SDCA_ CSG	Total	MED_ CSG	SDCA_ CSG	Total
DFM	2,806	2,806	5,612	2,806	2,806	5,612	2,506	2,506	5,012
JP5	3,034	3,034	6,068	5,146	5,146	10,292	4,084	4,084	8,168
STOR	61	61	122	61	61	122	61	61	122
ORDN	2.75	2.75	5.5	166	166	332	54	54	108

Table 1. Baseline scenario daily commodity consumption rates. Data is grouped in columns, first by scenario phase (Transit, Assault, Sustain) then by task unit (individual and combined). Each row contains the daily consumption of one commodity group in abstract *c*-units. For example: to find the total daily demand for ORDN during the Assault phase, one need only find the Assault group, then look down the "Total" column to the row labeled ORDN, where we see that a combined 332 tons of ORDN is consumed by both task groups during every day of the Assault phase.

Having set a baseline for combatant forces and their associated commodity requirements, we turn to establishing the minimum level of CLF support required to complete the mission. Current practice is for a deploying CSG to be assigned either a single T-AOE class ship or a T-AO class ship and T-AKE class ship operating in tandem for support. Taking this as an initial starting point, the model was run with three shuttles available: one T-AOE, one T-AO, and one T-AKE. While, the T-AOE begins the scenario in company with MED_CSG and the T-AO and T-AKE begin in company with SDCA_CSG, all CLF ships are left free to service either task group. The results of this initial run are presented as Figures 6 and 7.

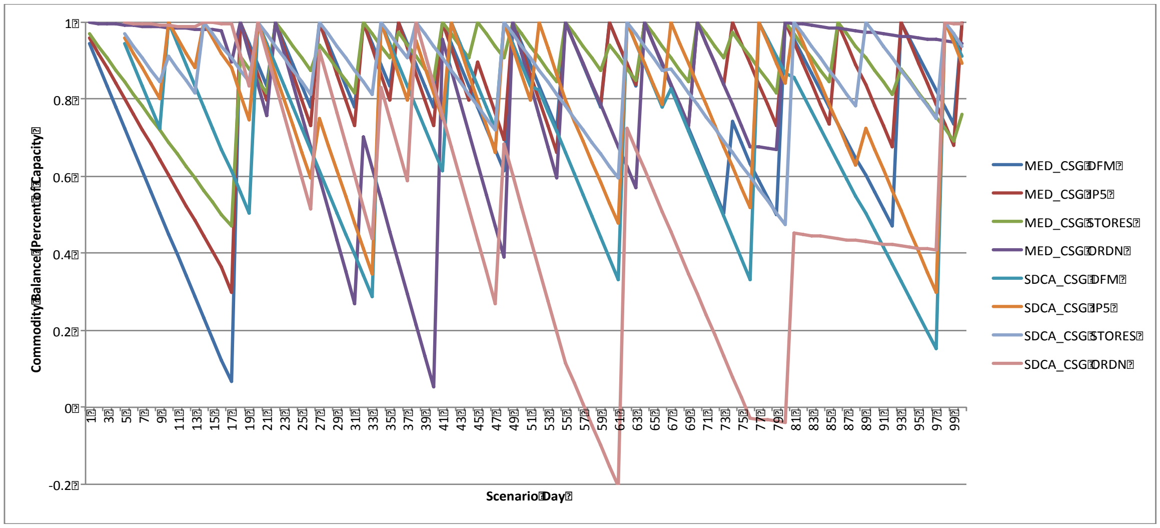

Figure 6. Daily commodity levels, baseline combatants with T-AOE, T-AO, T-AKE. All commodities represented.

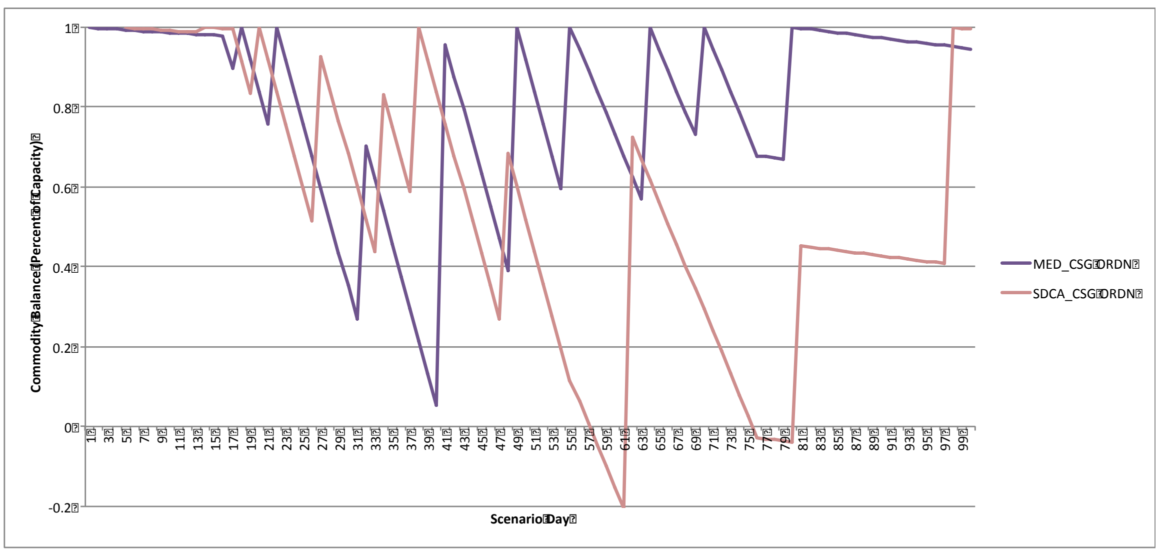

Figure 7. Daily ORDN levels, baseline combatants with T-AOE, T-AO, T-AKE. Same data as in Figure 6, but showing only ORDN for clarity. At its lowest point (day 61), SDCA_CSG achieves a negative balance in ORDN equal to 20% of its total capacity.

Figure 6 clearly shows our initial CLF assignments to be inadequate for this scenario, with SDCA_CSG spending multiple days with a negative ORDN balance during the sustainment (days 56–100) phase. For additional clarity, Figure 7 shows only ORDN levels throughout the scenario. Note that the overall trend in SDCA_CSG's

ORDN level after day 61 is positive, indicating that our assigned CLF forces may in fact be adequate for maintaining operations of that tempo in the long term. In contrast, the overall trend during the assault (days 18–55) phase is sharply negative, suggesting that the real shortfall occurs during the assault phase. If SDCA_CSG were to finish the assault phase with an ORDN on-hand balance higher than the 6.2% in the present solution, the three assigned CLF ships appear to be adequate for the demands of the sustain phase. To address this, the model was rerun with a dedicated ammunition ship (T-AE) added during the assault phase. The resulting sawtooth diagram is presented as Figure 8.

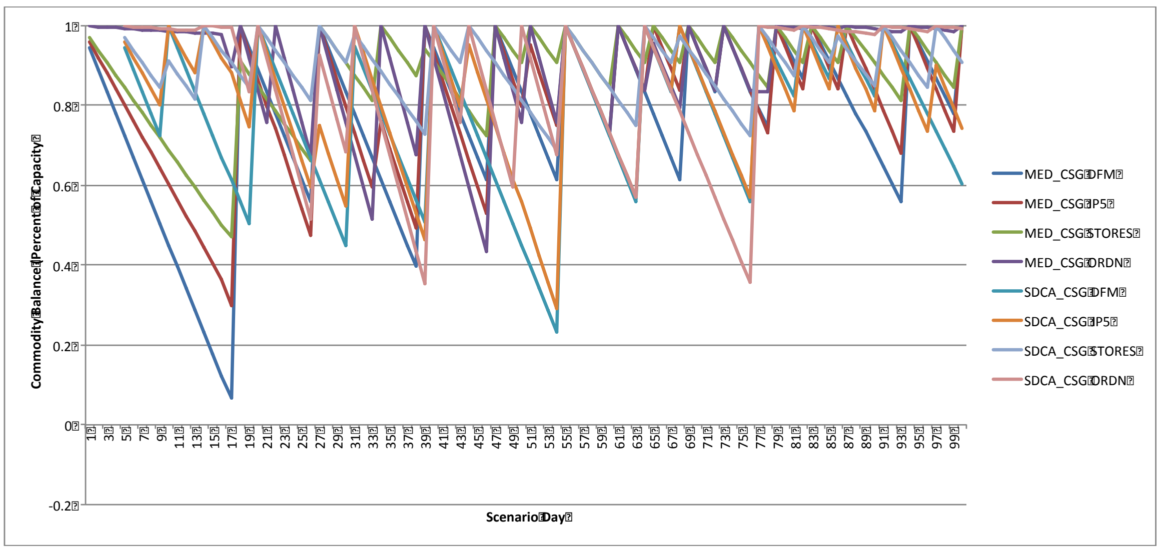

Figure 8. Daily commodity levels, baseline combatants with T-AOE, T-AO, T-AKE, T-AE. All four commodity groups are represented. Note that at its lowest point (day 40 and again at 77) ORDN now reaches a minimum of 35%; a value well above our extremis threshold of 25%.

As Figure 8 shows, the addition of a single T-AE during only the assault phase is sufficient to prevent any task group from suffering a negative balance in any commodity. Therefore, our "minimum feasible support requirements" for the baseline scenario is one T-AOE, one T-AO, one T-AKE, and one additional T-AE during only the assault phase of the campaign. Given this level of support, the baseline combatant package yields danger and extremis rates as shown in Table 2. These measure the fraction of time that each task group spends below the established danger and extremis thresholds of 50% and

25% for any commodity, with lower fractions being better. Table 3 provides idle rates for each CLF ship by phase, representing the fraction of time each unit spends in an idle status during each phase. Because this figure represents "slack" time and thereby potential residual support capacity, higher fractions are considered better. The data contained in these tables form the basis to which our variations will be compared.

	Transit Phase		Assault Phase		Sustain Phase	
Task Group	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate
SDCA_CSG	0.0	0.0	0.211	0.026	0.067	0.0
MED_CSG	0.471	0.235	0.105	0.0	0.0	0.0
Average	0.235	0.118	0.158	0.013	0.033	0.0

Table 2. Danger and extremis rates, baseline combatants and CLF support. Figures represent the proportion of time the specified task group spends below the specified threshold for any commodity group during the listed phase. E.g., during the 17-day Transit phase, the MED_CSG task group spends a total of 8 days below the 50% danger threshold for one or more commodity groups. The resulting danger rate is (8/17), or 0.471.

	Operational Phase		
Unit	Transit	Assault	Sustain
MED_AOE	0.0	0.18	0.22
SDCA_AO	0.0	0.21	0.31
SDCA_AKE	0.0	0.24	0.40
TAE_1	n/a	0.37	n/a
Average	0.0	0.25	0.31

Table 3. Baseline scenario CLF ship idle rates by phase. Figures represent the total proportion of time each CLF ship spends idle during each phase. E.g., during the 45-day Sustain phase, unit SDCA_AKE spends a total of 18 (generally non-contiguous) days in idle status. The resulting idle rate is (18/40), or 0.40.

B. VARIATION ONE: ONE CVN PLUS THREE CVL'S WITH TRADITIONAL ESCORTS

The first variation examines the impact of replacing the nuclear carrier at the heart of one task group with three smaller, conventionally powered replacements. Citing the considerable procurement costs and vulnerability to attack by comparatively inexpensive anti-ship missiles (Hughes, 2009), the NNFM concept calls for replacing three to five of the CVNs in the current U.S. fleet with ten smaller CVLs (Hughes, 2009, p. 30). By distributing carrier air power across a larger number of smaller platforms, both the unit cost and loss of operational capability in the event of a casualty are greatly reduced. Each CVL will be capable of supporting two squadrons of F-35B aircraft and will be approximately 25,000–30,000 tons in displacement. Since a Nimitz-class CVN supports 6 squadrons, we use three such CVLs in place of the CVN in order to provide a notionally equivalent level of air power.

In order to utilize this new ship in our model, we must first establish the consumption planning factors and capacities to be used. The first step in doing so is to settle on the tonnage and air wing size to be used. Table 4 provides an overview of six CVL-like ships in use by the US and other navies. The average displacement of these six ships is roughly 34,670 tons, and they are capable of supporting an average of 23.3 aircraft. Because these numbers are not greatly different than the stated NNFM design goals, we adopt them (rounding the aircraft up to 24) to be our notional CVL.

Class	Country	Displacement	Air Wing Size
Illustrious	UK	20,600	24
Juan Carlos I	Spain	27,079	20
Cavour	Italy	27,100	20
Charles De Gaulle	France	42,500	30
America (LHA-6)	USA	44,850	23
Kuznetsov	Russia	45,900	22
Average		*34,671.5*	*23.3*

Table 4. Displacement and air wing size of candidate light aircraft carriers. Data from Jane's Fighting Ships (2011).

With a notional size established, we turn to estimating consumption rates and capacities for the four commodity groups tracked by the CLF Planner. Because JP5 and ORDN consumption for a carrier are driven by the size of the embarked air wing, these were assumed to be one third of established CVN levels per CVL. Because our goal is to examine logistic supportability, not combat capability, capacities for these ships were also set to one third of those for a CVN in keeping with our assumption that three CVL can provide equivalent power projection to one CVN in terms of sortie hours and ordnance delivered.

STORES consumption is solely a function of crew size. To determine an estimated crew size, we turn to the work done by Juan Carrasco (2009) in analyzing the potential manpower requirements of the NNFM. Using simple linear regression to model ship crew size as a function of tonnage for existing carrier platforms, Carrasco determined that crew size was well approximated as *crew size = 0.0339 * displacement - 89.405* (Carrasco, 2009, p. 44). He then modeled air wing manning as a function of the number of aircraft assigned, finding *air crew size = 44.322 * (aircraft supported) - 425.07* to provide a reasonable fit **(**Carrasco, 2009, p. 46). Applying these two formulae to our notional CVL of 34,670 tons and 24 aircraft, we arrive at a total crew size of 1,721 (1,083 ship's company + 638 air crew). Existing STORES planning factors obey a rough rule-of-thumb of 1 short ton per 150 crewmembers per day. With a crew size of 1,721, this leads to an estimated STORES consumption rate of 11 short tons per day. The same existing planning factors suggest that US warships carry sufficient stores to support their crews for between 28 (CG) and 35 (DDG) days. We split the difference and assume our new CVL will have 32 days' STORES endurance.

A similar approach was taken for DFM consumption, although this proved to be a thornier problem. A simple regression analysis was conducted in two phases. The first phase sought to determine how much fuel is required to provide power for basic "hotel services" such as air conditioning, lighting, and water generation that can be assumed to remain relatively constant while the ship is underway regardless of its specific operations profile. The second phase fit a relationship between tonnage and the difference between existing fuel consumption rates and the hotel services load. Because logistics planning factors for foreign carriers were not available, existing consumption rates for gas turbine powered combatants (FFG, DDG, CG) were used instead.

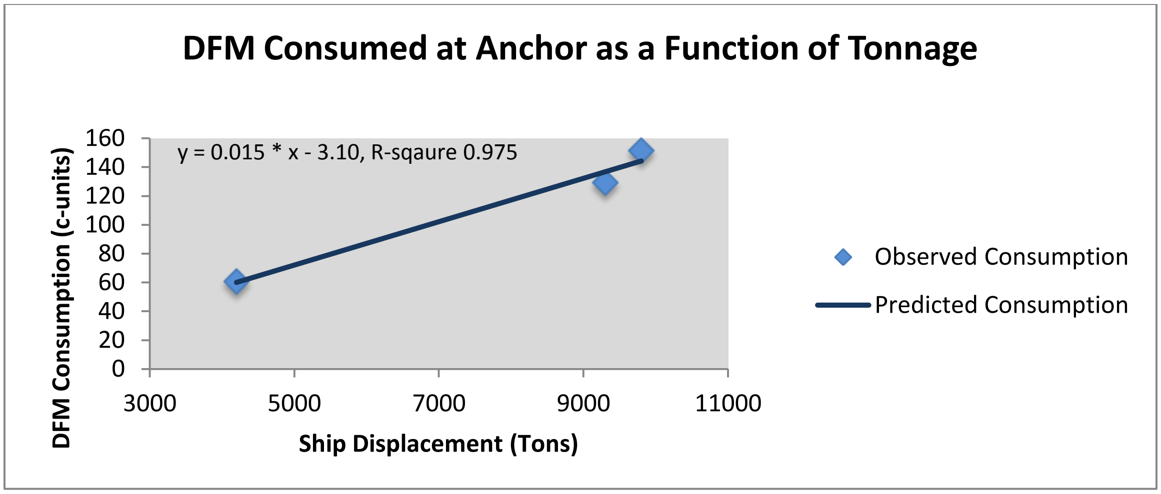

Figure 9. DFM consumption in "AtAnchor" status as a function of ship tonnage. Consumption of fuel while at anchor is used as a measure of the amount of fuel required to maintain basic "hotel services" such as power and fresh water generation.

Figure 9 depicts the results of the first phase analysis. The resulting model appears to fit well, with an R^2 value of 0.975. Applying this formula to our notional CVL yields an estimated DFM burn rate of 516.95 barrels per day, a deeply troubling figure more than two and one half times the 214.2 barrels per day required by the current *Wasp*- and *Tarawa*-class amphibious assault ships of similar size to our notional CVL at roughly 40,000 tons. Though their reliance on steam turbines for propulsion makes them poor choices for inclusion in our regression, it is difficult to believe that such a vast discrepancy exists in efficiency between steam and gas turbine based power generation. This in turn suggests that there may be economies of scale in play that are not captured by our simple model with its limited number of data points, and so we reject the results of this model and instead adopt a conservative estimate of 300 barrels per day.

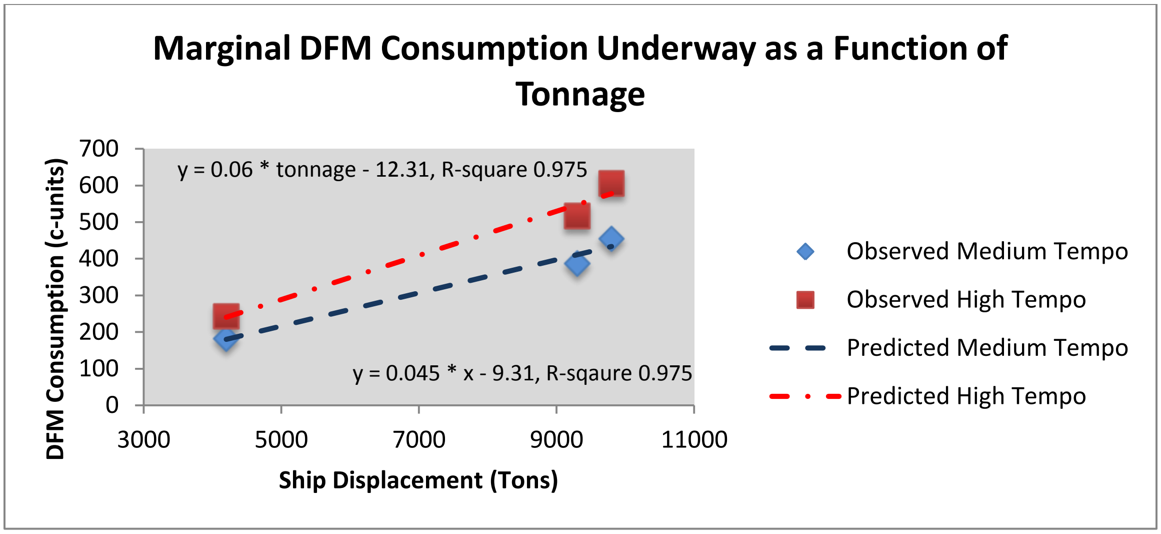

Figure 10. Marginal DFM consumption by operational category and tonnage. The upper line represents DFM consumption as a function of ship tonnage for high tempo (e.g., assault) operations. The lower line shows DFM consumption as a function of ship tonnage for medium tempo (e.g., station-keeping) operations.

Figure 10 depicts the results of the second phase of analysis. Two regressions are shown; one for the "OnStation" employment category and one for the "InTransit," "Assault," and "Sustain" categories, which current planning factors consider to be the same from a DFM consumption perspective. Again, both models fit well—as expected with so few data points to consider - with R^2 values of 0.975. From these regressions, we estimate that the incremental increase in fuel consumption (x) between hotel services and actual operations can be expressed by the equation *x = 0.045 * tonnage - 9.31* for medium tempo station keeping operations and by the equation *x = 0.06 * tonnage - 12.31* for high tempo operations. Applying these equations to our notional CVL and adding the estimated 300 barrels per day for hotel services yields estimated DFM burn rates of 1,850.8 barrels per day while station keeping and 2,367.8 barrels per day while conducting high-tempo operations.

We once again turn to the *Wasp* and *Tarawa*-class amphibious assault ships for a sanity check. These 40,000-ton steam turbine powered ships are similar in both size and shape to a small aircraft carrier, though their top speed of approximately 24 knots is substantially less than the 30-plus knots required of an aircraft carrier (Jane's Fighting

Ships, 2011). Assuming a notional top operational speed of 36 knots for our CVL, we expect it to consume on the order of $(1.5)^3$, or 3.375, times as much fuel as the *Wasp* and *Tarawa*-class amphibious assault ships require at 24 knots based on the generally accepted principle that the power (and therefore to a rough approximation fuel) required to move a ship through the water increases with the cube of speed (Comstock, 1944). The DFM consumption rate of the two large amphibious assault ships during high-tempo operations is 1,072 barrels per day. Applying the multiplier of 3.375 to account for the higher speeds required of the CVL, we would expect a daily DFM consumption rate of roughly 3,500 barrels per day if our CVL relied on steam turbines for propulsion. Compared to this, our predicted DFM consumption of 2,367.8 barrels per day for a gas turbine powered CVL seems a reasonable figure given the higher efficiency of the propulsion system used and we therefore adopt it as our planning factor. As with STORES, capacity is set a median value based on days endurance of other U.S. naval combatants; in this case, enough to sustain 17 days of sustained transit operations.

	Transit Phase			Assault Phase			Sustain Phase		
Commodity (Delta)	MED_ CSG	SDCA _CSG	Total	MED_ CSG	SDCA _CSG	Total	MED_ CSG	SDCA _CSG	Total
DFM	2,806	9,909	12,715	2,806	9,909	12,715	2,506	8,783	11,289
JP5	3,034	3,034	6,068	5,146	5,146	10,392	4,084	4,084	8,168
STOR	61	41	102	61	41	102	61	41	102
ORDN	2.75	2.75	5.5	166	166	332	54	54	108

Table 5. Daily consumption rates, CVN + 3 CVL with traditional escorts variation. As with Table 1, data is grouped in columns, first by scenario phase, then by task group. Task group SDCA_CSG now consists of three CVLs with two CGs and two DDGs as escorts. All values are in *c*-units. Note the substantial (7,100 *c*-unit) increase in DFM consumption that results from using three CVLs in place of the CVN in the SDCA_CSG task group.

Using these planning factors, we arrive at the projected daily commodity requirements in the Table 5. In this variation, SDCA_CSG is now composed of three CVLs accompanied by the same two CGs and two DDGs used in the baseline. The largest change is found in DFM required, which was to be expected given the exchange of a nuclear-powered carrier for three conventionally powered ones. CLF Planner was then run with these new consumption figures and the baseline CLF support package of one T-AOE, one T-AO, one T-AKE plus an additional T-AE during the Assault phase. This produced the sawtooth chart in Figure 11 and danger and extremis rates summarized in Table 6.

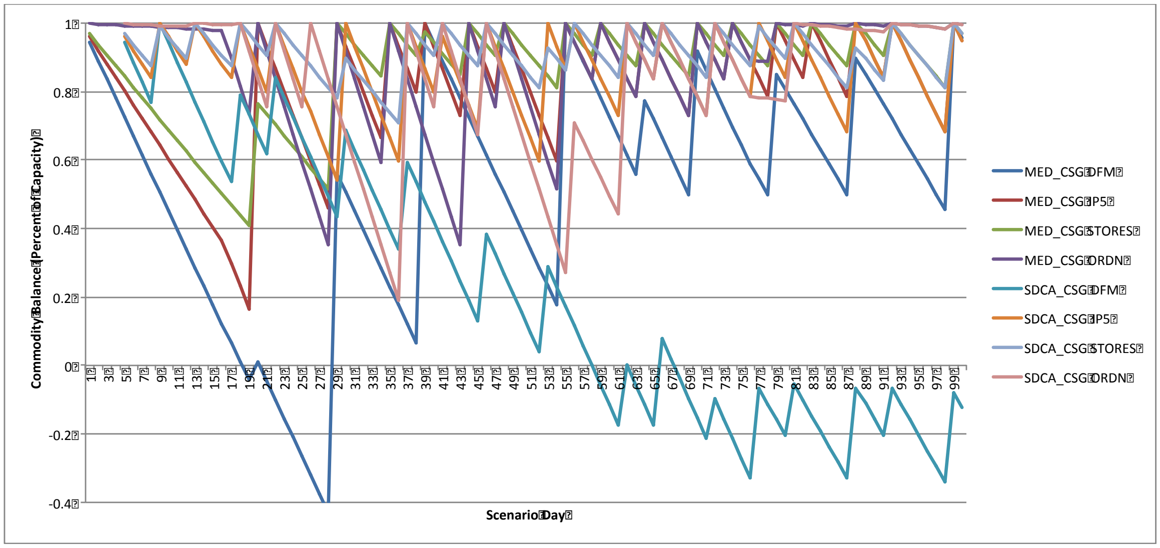

Figure 11. Daily commodity balance levels, CVN + 3 CVL with traditional escorts and T-AO, T-AKE, T-AOE, and T-AE (assault phase only) for support. As expected, the additional DFM demands of this scenario create significant challenges for the CLF–shown here by extended periods of negative DFM inventory balance for both task groups.

	Transit Phase		Assault Phase		Sustain Phase	
Task Group	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate
SDCA_CSG	0.0	0.0	0.605	0.263.	1.0	1.0
MED_CSG	0.471	0.235	0.711	0.447	0.111	0.0
Average (Delta from Baseline)	0.235 (0.0)	0.118 (0.0)	0.658 (+ 0.5)	0.355 (+0.342)	0.555 (+0.522)	0.5 (+0.5)

Table 6. Danger and extremis rates, CVN + 3 CVL with baseline CLF support. Fractions represent the proportion of time each task group spends below the danger and extremis thresholds for any commodity group. "Delta from baseline" shows the difference in rate as compared to the baseline (2 CVN, traditional escort) scenario.

Figure 11 and Table 6 clearly demonstrate that the baseline CLF assignment of one T-AOE, one T-AO, one T-AKE and one T-AE (during the assault phase only) is inadequate to support a CVL-based task group in this scenario. As suspected, the inability to provide an adequate amount of DFM drives the shortfalls, with both task groups spending significant amounts of time “dead in the water” due to negative DFM balances. The CVL-based task group, SDCA_CSG, is particularly hard hit, spending virtually the entire Sustain phase with a negative DFM balance. When able to function, our combatant ships are sorely lacking in flexibility, spending a majority of the Assault and Sustain phases below the danger threshold. Although able to execute their assigned missions in this state, any change in tasking that would present a net increase in logistical strain would almost certainly make an already unsatisfactory situation even worse.

Clearly, additional CLF support will be needed to make this variation of the scenario viable. Figure 11 shows DFM to be the obvious driver, but the question is how much additional support will be required? Unlike ORDN in the baseline scenario before adding the T-AE, here we see a negative trend in overall DFM levels during both the assault and sustain phases. This indicates that both phases will require additional support, although the shallow slope of the trend line in the sustain phase suggests that the level of additional support required by that phase is modest. With this in mind, CLF Planner was re-run with two additional T-AOs available—making three in total, one per CVL—during the assault phase and a single additional T-AO available during the sustain phase.

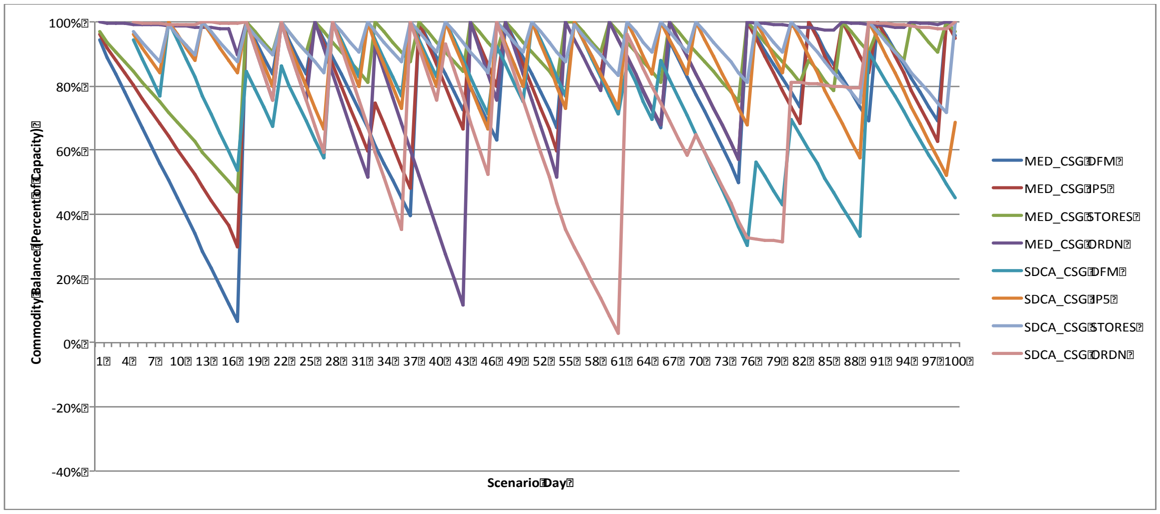

Figure 12. Daily commodity balance levels, CVN + 3 CVL with traditional escorts and augmented CLF support. In addition to the original T-AO, T-AKE, T-AOE, and T-AE of the baseline scenario, this variation features an two additional T-AOs (three in total) during the assault phase and one additional T-AO (two in total) during the sustain phase.

	Transit Phase		Assault Phase		Sustain Phase	
Task Group	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate
SDCA_CSG	0.0	0.0	0.105	0.0	0.444	0.111
MED_CSG	0.471	0.235	0.184	0.053	0.022	0.0
Average (Delta from Baseline)	0.235 (0.0)	0.118 (0.0)	0.145 (- 0.013)	0.026 (+0.013)	0.233 (+0.200)	0.056 (+0.056)

Table 7. Danger and extremis rates by phase, CVN + 3 CVL with traditional escorts and augmented CLF support. Delta from baseline figures suggest mission flexibility between this variation and the baseline scenario to be roughly equal the assault phase, and slightly degraded during the sustain phase.

The data in Figure 12 show that this variation now meets our definition of minimum feasible support, with no task group achieving a negative balance in any commodity group. Moreover, we see from the data in Table 7 that we are, in fact, achieving a comparable level of combatant mission flexibility. The slight difference in average danger and extremis rates during the assault phase is the result of only a single additional day below threshold by one task group, which for our purposes is equivalent. We do see a pronounced increase average danger rate during the sustainment phase, suggesting some reduced level of flexibility as a result of DFM shortfalls. The slight increase in extremis rate is driven by low ORDN levels early in the sustain phase. As the T-AE assigned to support the assault phase had ample ORDN available to meet this demand, this should not be viewed as a serious deficiency. In practice, the T-AE would have been held over into the sustain phase to make this delivery before departing the theater. Because CLF Planner makes the generally reasonable assumption that once an ship enters the scenario it will remain throughout the current planning horizon, we removed the T-AE order to maximize comparability between sustain phase results.

	Operational Phase		
Unit	Transit	Assault	Sustain
MED_AOE	0.0	0.26	0.36
SDCA_AO	0.0	0.21	0.27
SDCA_AKE	0.0	0.29	0.49
TAE_1	n/a	0.11	n/a
TAO_1	n/a	0.42	0.27
TAO_2	n/a	0.47	n/a
Average	0.0	0.293	0.348

Table 8. CLF idle rates by phase, CVN + 3 CVL with traditional escorts. Scenario phases are grouped in columns, each CLF ship is assigned a row. Ships that are not utilized in a given phase are listed as ‘n/a’. For example, the additional T-AE is only required during the assault phase and therefore shows ‘n/a’ under the transit and sustain columns.

Table 8 summarizes the CLF idle rates associated with this variation. We note no significant increase in excess support capacity during the assault phase even with two additional T-AOs (three in total) assigned. The average proportion of time CLF ships spend idle during the assault phase increases by only 0.043, from 0.25 in the baseline variation to 0.293. While this does represent an improvement, it translates to less than 1.5 additional idle days per month of operations. This is enough time to perform one additional consolidation if the CLF ship in question does not have to sail more than twelve hours out of its way to make the rendezvous, provided that the CLF ship in question also has sufficient stores on hand to meet that customers’ needs. While this additional time may become significant in aggregate, at the individual unit level it is of negligible consequence.

The situation in the sustain phase is similar, with the average CLF idle rate increasing from 0.31 in the baseline to 0.348. Despite the additional T-AO assigned, all CLF ships remain tasked at near capacity. From these findings, we conclude that the additional logistical load imposed by the transition to smaller, conventional carriers *cannot be made good out of excess capacity inherent in the current CLF employment strategy* and that either additional dedicated assets or a new type of oiler will be required. A more thorough discussion of these alternatives is found in Chapter V.

C. VARIATION TWO: TWO CVN WITH NNFM-STYLE ESCORTS

The next variation to be explored revolves around the new small surface combatants proposed by the NNFM study. Replacing some portion of the current inventory of multi-billion dollar multipurpose destroyers and cruisers with smaller, less expensive purpose-built surface combatants would enable the Navy to provide the increased forward presence the new U.S. maritime strategy requires (Hughes, 2009). Further, Hughes argues that from an employment perspective these small ships could be mixed and matched to counter a specific threat in a highly efficient way while at the same time their significantly reduced cost would lessen the economic risk associated with using them for their intended purpose—as warships. Six such classes of small combatants are proposed to provide specific capabilities across a range of missions including anti-submarine warfare, naval gunfire support, deep strike, ship-to-ship combat and counter-mine operations.

Designating a specific threat so that the correct package of escorts could be put together to defend against it, however, complicates our goal of creating a scenario that is easily generalized, and thus some simplification is needed. The new small combatant ship classes proposed by the NNFM are generally of frigate size (approximately 4,000 tons) and smaller. At 4,200 tons displacement, the *Perry*-class FFG is as large as any of the proposed new surface combatants and already has commodity consumption rates built into CLF Planner. This offers a convenient upper bound for the demands of the small NNFM surface combatants, which we adopt. For modeling purposes, further distinctions are not drawn between the various specific new ship types.

	Transit Phase			Assault Phase			Sustain Phase		
Commodity	MED_ CSG	SDCA_ CSG	Total	MED_ CSG	SDCA_ CSG	Total	MED_ CSG	SDCA_ CSG	Total
DFM	2,806	2,204	5,010	2,806	2,204	5,010	2,506	1,968	4,474
JP5	3,034	3,043	6,077	5,146	5,170	10,316	4,084	4,104	8,188
STOR	61	60	121	61	60	121	61	60	121
ORDN	2.75	2.66	5.41	166	159	325	54	52	106

Table 9. Daily commodity requirements, two CVN with NNFM-style escorts variation. Data is grouped in columns by scenario phase then task group. Task group SDCA_CSG now consists of one CVN with two DDGs and three FFGs as escorts.

For this variation, SDCA_CSG is composed of one CVN, 2 DDGs, and 3 NNFM combatants, represented in the model by FFGs. Table 9 summarizes the resulting daily commodity requirements. Compared to the baseline statistics in Table 1, we find total DFM consumption changed by the largest amount. The modified SDCA_CSG task group now requires approximately 20% less DFM than the unmodified MED_CSG group. This results in a ten percent decrease in overall fuel consumption for the scenario as a whole. Consumption of the other commodities tracked remains essentially unchanged, with projected reductions of less than 2.5%. Accordingly, it is reasonable to expect that the projected overall performance will be at worst equivalent to and perhaps slightly better than that of the baseline.

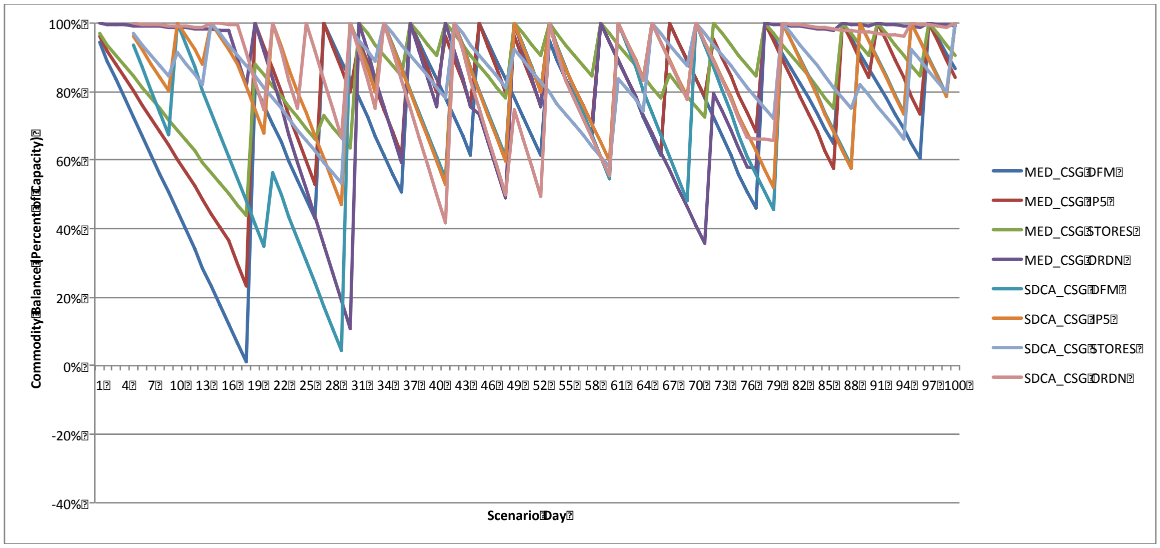

Figure 13. Daily commodity balance levels, 2 CVN with NNFM-style escorts variation. The impact of reduced combatant capacities is strongly evident at the end of the transit phase (day 18), where DFM levels as a percentage of capacity are noticeably lower than in the baseline scenario (Figures 6 and 8) despite an overall reduction in consumption rate.

	Transit Phase		Assault Phase		Sustain Phase	
Task Group	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate
SDCA_CSG	0.0	0.0	0.342	0.105	0.044	0.0
MED_CSG	0.471	0.235	0.210	0.079	0.089	0.0
Average (Delta from Baseline)	0.235 (0.0)	0.118 (0.0)	0.276 (+ 0.118)	0.092 (+0.079)	0.067 (+0.034)	0.0 (+0.0)

Table 10. Danger and extremis rates by phase, 2 CVN with NNFM-style escorts. Fractions represent the proportion of scenario time the specified task group spends below the danger and extremis thresholds in any commodity group.

Figure 13 and Table 10 show the performance of the model once NNFM-style escorts are introduced. As expected, given the reduced consumption rates when compared to the baseline scenario, the same CLF assignment of one T-AOE, one T-AO, one T-AKE, and one T-AE (during the assault phase only) of the baseline scenario is capable of delivering adequate support to complete assigned tasking in this variation. The notable increase in the proportion of time spent below the danger and extremis thresholds during the assault phase shown in Table 10, however, indicates a lack of mission flexibility when compared to the baseline scenario

We first examine the daily on-hand balances shown in Figure 13 for clues as to why this variation fails to offer comparable combatant flexibility when compared to the baseline scenario despite having lower overall daily commodity requirements. The height of the peaks in the sawtooth pattern indicates that each task group is generally at capacity following each consolidation event, which is a sign of adequate CLF storage capacity. Mobility of the CLF ships does not appear to be an issue, either, with the fine pitch of the sawtooth pattern indicating that replenishment events are happening frequently. The CLF idle rate data in Table 11 provides further evidence that our CLF ships are not overly taxed in providing this level of service. During the assault phase, the average proportion of time our CLF ships are idle increases from .253 to .303, indicating that the CLF workload is actually lighter during this phase as compared to the baseline scenario.

	Operational Phase		
Unit	Transit	Assault	Sustain
MED_AOE	0.0	0.26	0.13
SDCA_AO	0.0	0.32	0.07
SDCA_AKE	0.0	0.21	0.40
TAE_1	n/a	0.42	n/a
Average	0.0	0.303	0.20

Table 11. CLF idle rates by phase, two CVN with NNFM-style escorts. Fractions represent proportion of time spent idle by the specified CLF ship during the listed phase.

Having evidence of sufficient capacity and mobility, the exact reasons why this variation did not perform as well as the baseline are still unclear. One possible explanation is that the smaller ships postulated by the NNFM, while requiring less support in terms of *c*-units consumed, also hold less materiel and likely will require more frequent replenishment. It is also possible that the observed effect is peculiar to this specific scenario. Still, it is safe to say that at a minimum in a wartime scenario such as the one examined here, the small reductions in consumption are not enough to significantly reduce the amount of logistical support required.

D. VARIATION THREE: ONE CVN PLUS THREE CVL WITH NNFM-STYLE ESCORTS

The final variation explores the integration of the previous two. For this variation, we replace both the CVN and escorts of SDCA_CSG with NNFM equivalents. To account for the lack of flexibility incurred by replacing all of the multi-mission CG and DDG escorts with purpose-built NNFM-style platforms, the total number of escorts assigned is increased to nine. As in the two CVN with NNFM-style escorts variation, FFG consumption factors are used to model NNFM combatants. The daily commodity requirements of this fleet configuration are shown in Table 12.

	Transit Phase			Assault Phase			Sustain Phase		
Commodity	MED_ CSG	SDCA _CSG	Total	MED_ CSG	SDCA_ CSG	Total	MED_ CSG	SDCA_ CSG	Total
DFM	2,806	9,839	12,645	2,806	9,839	12,645	2,506	8,720	11,226
JP5	3,034	3,076	6,110	5,146	5,306	10,452	4,083	4,189	8,272
STOR	61	42	103	61	42	103	61	42	103
ORDN	2.75	2.68	5.43	166	159	325	54	52	106

Table 12. Daily commodity requirements, CVN plus three CVL with NNFM-style escorts. Data is grouped in columns by scenario phase then task group. In this variation, task group SDCA_CSG consists of three CVLs with a total of nine FFGs as escorts.

At 12 total ships—three CVLs and nine FFGs—the resulting SDCA_CSG task group would be difficult for a single CLF ship to service in one day. To account for this the SDCA_CSG task group was broken up into two groups, forcing two separate replenishment events and thus two days of schedule time to completely resupply. In order to ensure consistent measures of comparison with the other variations, the projected daily balances output by the model were summed to a single number representing the task group as a whole, which was then used to calculate the danger and extremis rates of the entire task group. Conceptually, this is no different from what the CLF Planner already does when computing task group requirements and balances based on the specified component ships, and thus the resulting statistics are equally valid. CLF ships were assigned in the same way as the CVN plus three CVL with traditional escorts variation: one T-AO, one T-AKE, and one T-AOE are available throughout the entire scenario, with one additional T-AE and two additional T-AOs (three in total) available during the assault phase and one additional T-AO (two in total) available during the sustain phase. Figure 14 and Table 13 provide the summary results of running the model in this configuration.

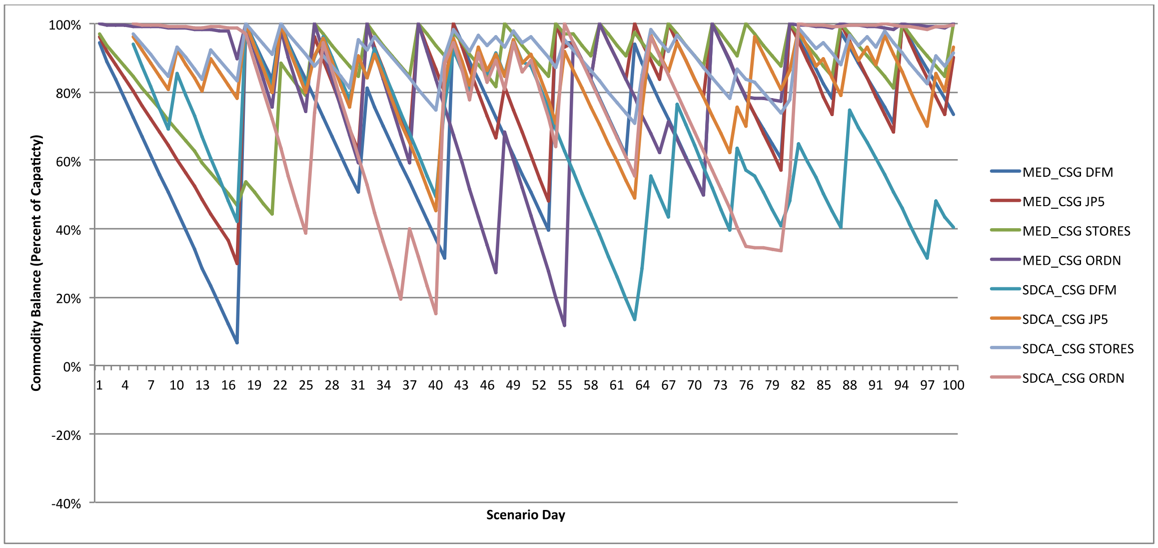

Figure 14. Daily commodity balances, CVN plus three CVL with NNFM-style escorts. Each line shows the daily on-hand balance of one commodity group for one task group.

	Transit Phase		Assault Phase		Sustain Phase	
Task Group	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate	Danger Rate	Extremis Rate
SDCA_CSG	0.0	0.0	0.263	0.079	0.6	0.044
MED_CSG	0.471	0.235	0.368	0.053	0.022	0.0
Average (Delta)	0.235 (0.0)	0.118 (0.0)	0.315 (+ 0.157)	0.066 (+0.053)	0.311 (+0.278)	0.022 (+0.022)

Table 13. Danger and extremis rates by phase, CVN plus three CVL with NNFM-style escorts. Data is grouped in columns by scenario phase then task group. Fractions represent the proportion of scenario time the specified task group spends below the danger (50%) and extremis (25%) thresholds in any commodity group. Delta represents the difference between the average value in this variation and that of the baseline scenario.

Based on the similar daily commodity requirements outlined in Tables 5 and 12, this variation is expected behave similarly to the CVN plus three CVL with traditional escorts variation. Visual comparison of the results in Figures 12 and 14, however, reveals that support becomes much more challenging during the sustain phase in this variation. Using the height of the sawtooth peaks as a guide, replenishment events in the first variation generally result in the combatant ship being refilled to capacity. In this variation, however, we routinely see only partial replenishments. Also of note is the clear downward trend in DFM for the SDCA_CSG task group at the end of the sustain phase, indicating that these operations would not be indefinitely sustainable with the same set of CLF ships required for continued support of the CVN plus three CVL variation that utilizes traditional escorts despite an overall reduction in daily commodity requirements.

The proportion of time our combatants spend below the danger and extremis thresholds as shown in Table 13 adds further support to the hypothesis offered in the two CVN with NNFM-style escorts variation that the smaller capacities of NNFM-style escorts outweigh their reduced consumption requirements. At 0.278, the increase in proportion of time spent below the danger threshold is even greater than the increase observed in the one CVN plus three CVLs with traditional escorts variation. This suggests that, once again, despite an overall reduction in daily commodity requirements the smaller NNFM-style escorts are actually more difficult to support. Despite the significant capacity available in terms of both volume of materiel available and area that can be covered by the T-AOE and two T-AOs assigned during the sustain phase, the additional frequency of replenishment required by the smaller capacities of the NNFM-style escorts still appears to drive the problem.

	Operational Phase		
Unit	Transit	Assault	Sustain
MED_AOE	0.0	0.45	0.24
SDCA_AO	0.0	0.21	0.27
SDCA_AKE	0.0	0.29	0.24
TAE_1	n/a	0.34	n/a
TAO_1	n/a	0.39	0.29
TAO_2	n/a	0.29	n/a
Average	0.0	0.329	0.261

Table 14. CLF idle rates by phase, CVN plus three CVL with NNFM-style escorts. Fractions represent the proportion of time that the listed CLF ship spends not actively prosecuting a replenishment event during the specified phase.

The CLF idle rate data in Table 14 supports this finding. While a slight increase in average idle rate is observed during the assault phase, from 0.293 in the CVN plus three CVLs with traditional escorts variation to 0.329 here. Once again, an increase in idle rate of this magnitude translates to roughly only one additional idle day per month of operations. We also observe a substantial decrease in idle rate during the sustain phase, from 0.348 in the CVN plus three CVLs with traditional escorts variation to 0.261 here, equating to roughly 3.5 fewer idle days per month. Clearly, our CLF ships are far more heavily engaged in this variation despite having to keep pace with lower total daily demands.

V. CONCLUSIONS AND RECOMMENDATIONS

A. LOGISTICS SUPPORT MUST BE AN INTEGRAL PART OF ANY FUTURE PLAN

The U.S. Navy FY11 shipbuilding plan calls for a projected inventory of 19 T-AO (OPNAV N8F, 2010, p. 15). If we assume that each continental U.S. numbered fleet (2^{nd} and 3^{rd}) retains one T-AO and each forward deployed numbered fleet not directly involved in a conflict retains two each to support training and continued operations, an absolute maximum of 13 T-AO will be available for use in the theater of conflict. Working backwards from this limit it is clear that the ability of a fleet such as the one proposed by the NNFM study to conduct widespread operations will be substantially reduced. This is particularly true because the lightweight carriers that provide the flexibility in the proposed fleet will consume a considerable amount of fuel—unless they are nuclear powered, such as the French *Charles de Gaulle* (Jane's Fighting Ships, 2011).

Assuming a roughly fifty-fifty mix of CVN- and CVL-based strike groups, the maximum number of deployed strike groups that could be supported by 13 T-AO is six; three traditional CVN based (three T-AO) and three based on the three-CVL configuration explored here (nine T-AO). Note, however, that this arrangement leaves only a single T-AO to both service any independently operating units and to serve as a replacement should a carrier-assigned T-AO be lost. In practice, it is expected that more independent oilers would be required to service units performing such tasks as theater ballistic missile defense and maritime interdiction operations. As a result, additional CLF redundancy would be desired and deployable forces would be even further constrained. For example, assigning just four T-AO to these functions reduces our number of supportable strike groups in theater to four. Compared to the nine CVN groups that could notionally be supported by the same force, that represents more than a 50% reduction in combat power unless additional CLF ships are added.

The results of the variations here that explore the impact of using NNFM-style small combatants as escorts are far less conclusive. While the FFG used as a proxy to model the requirements of these small combatants represents a conservative estimate, this still offers a 10% reduction in overall fuel consumption. Given that this 10% reduction in demand produces no appreciable improvement, it seems unlikely that further reducing the size of the escorts by any reasonable amount will offset the significant DFM demands imposed by CVLs. Moreover, the results of the two CVN with NNFM-style escorts and CVN plus three CVL with NNFM-style escorts variations suggest that reduced storage capacities of these smaller combatants will require more frequent replenishments, offsetting their lower rates of consumption and making them harder, not easier, to support. In the war-at-sea scenario examined here, we must conclude that in the best case a larger number of NNFM-style escorts will be at least as challenging to support as the traditional set of CGs and DDGs that they are meant to replace.

While the quantitative results achieved are subject to wide bands of uncertainty due to the admittedly rough nature of the logistics planning factors used, it is abundantly clear that substantial additional logistical support will be needed to support the type of fleet proposed by the NNFM study. CLF ships are as subject to time and cost constraints as any other ship, and must be designed and built by someone, somewhere. Given strong evidence that the current CLF is not prepared to meet the challenges of supporting the smaller, conventionally powered CVLs that make the NNFM-style fleet possible and that the transition to smaller, purpose-built escort ships will do little to ease the burden, we must conclude that planning for an appropriate CLF must proceed in tandem with any further development of a distributed NNFM-style fleet. We cannot afford (in either sense) to wait until the fleet of the future is delivered before we decide how to support it.

B. THE FUTURE CLF MUST BE MORE NUMEROUS

If more capability is required, then there are two basic paths to get there: increase the amount that can be delivered at each replenishment event (volume) or increase the number of replenishment events that can occur (speed). In an ideal world we could have both, but we operate in a constrained environment and tradeoffs must be made. The ill-fated T-AOE(X) program is illustrative. Like the current T-AOE it was intended to replace, the T-AOE(X) combined high speed (26+ knots) with a full line of commodities, providing a highly mobile "one-stop-shop" for deploying task groups (Burgess, 2004). The estimated $1B price tag for this "no compromises" design proved too high, and the program was cancelled in 2005. In comparison, the T-AO and T-AKE platforms currently in use have a cost of approximately $500M (Cooper, 2010). The data collected for this research was inconclusive as to whether volume or speed represents the better investment, but as the T-AOE(X) program shows, we cannot afford both. One must come at the expense of the other.

If we remain attached to current unit costs and therefore CLF ship size, both alternatives suffer from the same weakness. Namely, the potentially catastrophic impact of the loss of even a single CLF ship could have on our operational capability. As an example, we point to our baseline scenario. Without the support of the single T-AE that was added during the assault phase, a whole task group is neutralized by lack of ordnance. The impact of the loss of a multi-commodity ship such as a T-AOE would be even greater. A capable foe will recognize this, and CLF ships will become prime targets in wartime. The situation is analogous to that of the CVN as detailed in the NNFM study, and we draw a similar conclusion: more numerous and less costly ships are preferred. Just like the NNFM study decision to replace few CVNs with many CVLs, having more ships reduces the effects of losing any one. More ships would also allow for a greater variety of CLF ship types, avoiding the size versus speed tradeoffs that killed the T-AOE(X) by simply having some of each as needed: smaller faster ships for applications which require speed (such as station ships that must keep up with a CSG) and larger, slower ships where quantity is most important (such as shuttle ships responsible for feeding multiple station ships.)

C. FLEXIBLE ANALYSIS IS BETTER

As George Box once said, "all models are wrong, some are useful." It is often tempting, especially when working with optimization problems, to attempt to build as complete a model as possible in an effort to find "the answer." Such was the original intent of this research. Although the desire to introduce and (more importantly) remove CLF ships *in situ* drove the shift to the final "phased" and manually aggregated approach, we have found several distinct advantages along the way that make it particularly attractive for analysis such as this.

To better understand these advantages, we must first understand the price we pay for them. By modeling the scenario in phases and manually aggregating the results, we accept that our composite solution will likely be "less good" than one that is truly globally optimal. The reasoning behind this assertion is simple; if there were some combination of locally optimal solutions that produced a better solution than our theoretical global solution in aggregate, that combination of local solutions would become the globally optimal one. Put another way, by its very definition the globally optimal solution forms the upper bound on what any aggregated set of local solutions can achieve. There is nowhere to go but down.

In exchange for this loss of global optimality, or "goodness," however, we gain tremendous flexibility. In the specific example of this research, that flexibility is the ability to adjust the model to respond to the changing needs of each phase by introducing and removing CLF ships to meet demand. Absent this flexibility, we would have been forced to provide the same level of support during each phase, potentially masking the true challenges posed by each. As an example, early exploratory runs suggest that the meager amount of DFM carried by a T-AE is enough to shift the slightly negative trend in DFM levels into a positive one during the Sustain phase of the CVL with traditional escort case. It is only by removing the T-AE that this important potential shortfall becomes visible, and it is our phased approach that makes this insight possible.

Additionally, the assertion that "there is nowhere to go but down" rests on the assumption that the aggregate solution is attempting to solve the same problem as the global. By manually decomposing our problem and aggregating our solution, however, we gain the flexibility to adjust the parameters of the model in response to the changing needs of the scenario. In CLF Planner, for instance, one could adjust the relative priority of each commodity based on the situation, such as by making ordnance more or less important depending on the level of combat operations taking place. We resisted this temptation in our analysis in order to ensure maximum comparability between runs, but the potential impact is significant and may do a great deal to make up for the loss of "goodness" we accept by choosing to pursue an aggregate solution.

A second advantage of a manually aggregated solution is increased transparency. Regardless of approach, decisions made by the solver will have repercussions that stretch throughout the planning horizon. When solving a model monolithically, the lag between these causes and effects can be significant and can lead to observed behaviors that are difficult for the analyst and logistician to understand. By shortening the planning horizon, we draw the cause and effect more closely together and more insight can be gained into why odd behaviors occur.

In summary, we recognize that decomposing into a piecewise solution to our scenario by modeling it in a series of separate phases will likely result in less than a theoretically optimal solution. However, we feel that any such deficiencies will be ameliorated by gains in transparency and the flexibility to adjust model parameters "on the fly." We are further rewarded by the additional insights that result from shortening the chains of cause and effect through shorter planning horizons. On the whole, we feel that these gains outweigh the costs of potentially lost optimality and recommend a similar approach be adopted when pursuing future research or operational plans.

D. FUTURE RESEARCH

Due to the painstaking, manually intensive nature of developing individual task group voyage plans over a broad planning horizon, this research focused on only a single scenario with a small number of task groups. Although adequate for answering the qualitative aspect of our question, it is incomplete. The need for additional CLF support is demonstrated, but this set of results is inconclusive for the questions of what combination of speed and capacity will best allow the CLF ship of the future to meet this additional need. The potential areas of research listed below are suggested to help add clarity to this issue.

1. Examine the Feasibility of Alternate Support Concepts

This research uses a "delivery boy" support concept where CLF ships transport commodities directly from logistics hubs to customers as it reflects the way replenishments at sea are currently scheduled. However, alternative delivery models exist. One such is the "station ship—shuttle ship" concept of support utilized in the recent past. Under this model a high-speed multi-commodity ship (the "station ship," traditionally a T-AOE) remains in close proximity to its assigned task group at all times to service combatant needs. Other "shuttle ships" are employed to service the station ship and the occasional combatant as needed. This offers numerous operational advantages, many of them outlined by the Congressional Budget Office (CBO, 1988, pp. 7–10). A more-numerous CLF would enable a return to this concept of support, and research should therefore be conducted into the best size and product mix for a station ship to make this concept desirable again.

2. Explore a Larger Range of Scenarios

The scenario examined here was chosen in large part because of the similarity in force employment between a traditional fleet and a fleet such as the one proposed by the NNFM study. While this led to an apples-to-apples comparison of support required to achieve a given level of combat power projection, it is not a scenario that is the most likely in practice. Moreover, it is only taxing in one dimension. While requiring a large volume of materiel to be delivered, it is not terribly difficult to support in terms of distances travelled. Additional research needs to be done exploring the support requirements of smaller units operating independently with greater geographic separation. In other words, when our fleet is forced to respond to multiple smaller contingencies at more widely separated locations. These small-scale, widely dispersed scenarios more accurately reflect the type of conflicts envisioned by *A Cooperative Strategy for 21st Century Sea Power* (SECNAV, 2007) and should be included in any definitive study of future CLF requirements.

3. Examine the Impact of the Littoral Combat Ship (LCS)

The LCS represents the Navy's present answer to the need for smaller, distributed warships like the ones proposed by the NNFM study. At 2,200 and 3,000 tons (Jane's Fighting Ships, 2011), the two competing designs are smaller than an FFG and are similar in size to most of the small combatant design archetypes proposed by the NNFM. Unlike the NNFM single-purpose NNFM combatants, the LCS achieves the flexibility of multi-purpose designs through the use of interchangeable mission modules (Jane's Fighting Ships, 2011).

At the time of this writing, logistics planning factors for these new ships have yet to be determined. Moreover, they employ both gas turbines and diesel engines to power a water-jet propulsion system (Jane's Fighting Ships, 2011) that is significantly different from the propulsion systems of any present U.S. warship for which we have established planning factors. Lacking any basis on which to build our own meaningful consumption estimates, we instead chose to use the well established FFG as the model for our hypothetical NNFM combatants.

The U.S. Navy has already made a commitment to buy at least 20 of these ships (Jane's Fighting Ships, 2011), however, and as a result the LCS will must be a part of any future fleet planning over the next 20–30 years. Accordingly, we feel that incorporating this design into our model is an important next step—just as soon as appropriate logistics planning factors become available.

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